Improvement of the procedures for monitoring the positioning service of the National Land Survey

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Abstract of the master's thesis

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Abstract

The National Land Survey positioning service offers real-time correction data for code- and phase-based positioning. The service operates on the data of FinnRef reference stations. The data is used to model the error sources affecting GNSS observations. Based on the model, the service sends corrections to the users.
The aim of this thesis is to improve the performance of the NLS positioning service by improving its real-time monitoring procedures. The whole monitoring of positioning services is examined, starting from the observations of the reference stations and ending to the user positioning quality. This work defines relevant parameters that should be monitored and investigates different monitoring possibilities. From the possibilities, the ones most suited for the needs of the NLS are implemented.
As a result of this work, the applied improvements to the monitoring are presented: enabled internal monitoring procedures of the positioning service software (GNSMART) and the acquired software solutions for external monitoring. The internal monitoring possibilities include mainly alarms triggered by different processes. The external monitoring, mountpoint and positioning quality monitoring, is implemented with the software Alberding-QC. This software has been developed especially for positioning service operators.
One conclusion of this thesis recommends that the positioning quality monitoring is done with physical monitoring stations. The achievable positioning performance by using the service in Finland can be verified with 5-10 monitoring stations. In this work, the monitoring stations were not established, instead the software was tested using real-time observation data from available sources. The solutions are computed with the positioning software GNRT-K. The monitoring stations established in the future are recommended to be equipped with good equipment at locations in good observing environments, in order to better separate the quality of the used correction. On top of the monitoring framework established in this work, the monitoring of the NLS positioning service can be raised to a sufficient level.

Keywords GNSS, NRTK, monitoring, quality, integrity, positioning service, augmentation service, FinnRef

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Tiivistelmä

Maanmittauslaitoksen paikannuspalvelu tarjoaa reaaliaikaista korjausdataa koodi- ja vaihepaikannukseen. Palvelun toiminta perustuu FinnRef-referenssiasemien havaintodataan, jonka perusteella GNSS-havaintoihin vaikuttavat virhelähteet mallinnetaan ja mallista muodostetaan käyttäjille lähetettävät korjaukset.

Tämän työn tavoitteena on parantaa Maanmittauslaitoksen paikannuspalvelun toimivuutta kehittämällä sen tosiaikaista seurantaa. Paikannuspalveluiden seurantaa käsitellään kokonaisuudessaan alkaen tukiasemien havainnoista ja päättyen palvelun käyttäjän saavuttamaan sijaintitarkkuuteen. Työssä selvitetään mitä parametreja tulisi seurata sekä perehdytään erilaisiin seurantaratkaisuihin joista toteutetaan parhaiten Maanmittauslaitoksen tarpeita vastaavat.

Työn tuloksina esitellään toteutetut seurannan kehityskohteet: Käyttöön otetut paikannuspalveluohjelmiston (GNSMART) sisäiset seurantaominaisuudet sekä hankitut ohjelmistot ulkoiseen seurantaan. Sisäiset ominaisuudet sisältävät lähinnä eri prosessien laukaisemat hälytykset. Ulkoinen seuranta, eli mountpointtien ja sijaintiratkaisun seuranta, toteutetaan Alberding-QC-ohjelmistolla. Tämä ohjelmisto on kehitetty erityisesti paikannuspalveluiden tarjoajia varten.

Työn yhtenä johtopäätöksenä suositellaan sijantiratkaisun seuranta tehtäväksi fyysisillä seuranta-asemilla. Palvelulla saavutettava sijaintiratkaisun tarkkuus Suomessa pystytään varmistamaan 5-10 seuranta-asemalla. Tässä työssä seuranta-asemia ei vielä perustettu, vaan ohjelmistoja on testattu käyttäen tosiaikaista havaintodataa saatavilla olevista lähteistä. Näistä havainnoista on laskettu tosiaikaiset sijaintiratkaisut GNRT-K-laskentaohjelmistolla. Perustettavilla seuranta-asemilla suositellaan käytettävän riittävän hyviä laitteita sekä havaintoympäristöjä, jotta tuloksissa korostuu käytettävän korjauksen laatu. Tässä työssä perustetun seurannan rungon päälle MML:n paikannuspalvelun seuranta on helppo kehittää riittävälle tasolle.

Avainsanat GNSS, NRTK, seuranta, laatu, eheys, paikannuspalvelu, tehostuspalvelu, FinnRef

Contents

Abbreviations

AdV	Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der BRD
ARP	Antenna Reference Point
BKG	Bundesamt für Kartographie und Geodäsie
BRD	Bundesrepublik Deutschland
CMR	Compact Measurement Record
CNR	Carrier-to-noise ratio
CORS	Continuously Operating Reference Station
CRCSI	Cooperative Research Centre for Spatial Information
DGNSS	Differential GNSS
DGPS	Differential GPS
ECEF	Earth-Centered, Earth-Fixed
EPN	European Permanent Network
ETRS	European Terrestrial Reference System
EUPOS	European Position Determination System
FGI	Finnish Geospatial Research Institute
FKP	Flächenkorrekturparameter
GKÚ	Geodetic and Cartographic Institute of Slovakia
GLONASS/GLO	Globalnaja navigatsionnaja sputnikovaja sistema
GNSMART	GNSS State Monitoring and Representation Technique
GNSS	Global Navigation Satellite System
GOP	Geodetic Observatory Pecný
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
HTTP	Hypertext Transfer Protocol
i-MAX	Individualized Master-Auxiliary Corrections
IGS	International GNSS Service
IOC	Initial Operational Capability
IP	Internet Protocol
IRNSS	Indian Regional Navigation Satellite System
LAMBDA	Least-squares Ambiguity Decorrelation Adjustment
LDBV	Landesamt für Digitalisierung, Breitband und Vermessung
LSAST	Least-squares Ambiguity Search Technique
MAC	Master-Auxiliary Concept
MAX	Master-Auxiliary Corrections
MEO	Medium Earth Orbit
MSM	Multiple Signal Message
NKG	Nordiska Kommissionen för Geodesi, Nordic Geodetic Commission
NLS	National Land Survey (of Finland)
NMEA	The National Marine Electronics Association
NOVA	Network Online Visualisation of Accuracy
NRTK	Network Real Time Kinematic
Ntrip	Networked Transport of RTCM via Internet Protocol
OTF-AR	On-The-Fly Ambiguity Resolution

PCV	Phase Center Variation
ppm	Parts per million
PPP	Precise Point Positioning
PRC	Pseudorange Correction
PRS	Pseudo Reference Station
QC	Quality Control
RINEX	Receiver Independent Exchange Format
RRC	Range Rate Correction
RSIM	Reference Station Integrity Monitor
RTCM	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematic
RTQC	Real Time Quality Control
RTSP	Real Time Streaming Protocol
RTP	Real Time Transport Protocol
SBAS	Satellite-Based Augmentation System
SQL	Structured Query Language
SSR	State Space Representation
SV	Satellite Vehicle
TCP	Transmission Control Protocol
TTFA	Time To Fix Ambiguities
UDP	User Datagram Protocol
UDRE	User Differential Range Error
VCL	Virtual Component Library
VRS	Virtual Reference Station

1 Introduction

Satellite navigation and positioning is nowadays used in all levels of society. The number of Global Navigation Satellite System (GNSS) devices in use is forecasted to increase to almost eight billion by 2020 [13]. The past and ongoing development of several GNSS has improved the availability of positioning signals and accuracy achieved with all receiver types. The stand-alone positioning accuracy is however in the order of few meters which is why GNSS augmentation systems are used for improved accuracy. Common for these systems is the use of permanent continuously operating reference stations and the transmission of augmentation data to the user. In most developed countries there exists one or more networks of reference stations the data of which is used for a regional augmentation or positioning service operated by public and private sectors.

In many cases positioning services are used for official activities and critical applications, for which reason they should be constantly monitored to detect and minimize the risk of errors [43]. To be able to offer positioning service at high level, the service operator should have knowledge of the system performance which is gained by monitoring. The performance of a satellite navigation system or a positioning service can be characterized by a number of performance parameters such as availability, accuracy, continuity, integrity and reliability [24, p. 267][12, p. 74]. These indicators can be used as a guideline to formulate concrete parameters the state of which is represented by numerical values and can be used to monitor the positioning service performance.

This thesis focuses on the monitoring of a regional service, using the National Land Survey (NLS) positioning service as a case of which monitoring procedures are improved. The service produces real-time data streams that are used for differential GNSS and Real Time Kinematic (RTK) positioning. The aim of the thesis is to improve the performance of the NLS positioning service through real-time monitoring procedures. The problem can be characterized with the following research questions:

1. What should be taken into account in monitoring of a positioning service?
2. What kind of monitoring procedures and software exist?
3. What is the optimal monitoring solution for the NLS?

The first two research questions are answered by studying research made on positioning service monitoring and positioning services themselves, and by testing different software possibilities. The answer for the first question is given as a set of relevant monitored parameters describing the system state. The third research question is answered based on the parameters and solutions examined for questions 1. and 2. This work suggests and partially implements the optimal monitoring solution for the NLS positioning service.

Earlier research on positioning service monitoring has been conducted mainly by surveying officials of different states, or is funded by them (e.g., [15][43][57]). Such research is reviewed in this work to present a view on possible monitoring implementations. Comprehensive research covering the complete positioning service monitoring task has not been done, most research focuses on one task, for example positioning quality achieved by using the service. This thesis aims to present and compare a variety of possible monitoring solutions. In some parts of this text more remarks are based on the writer's user experience with the positioning service software Geo++ GNSMART [69] and Topcon TopNET*live* [64].

Monitoring of a positioning service is closely related to the monitoring of GNSS signal quality. In this text these issues are treated separately so that the service monitoring is the main issue. Signal quality monitoring is noted as it is done inside the positioning service software, and a few other real-time possibilities for observation data monitoring are presented. Development of an independent monitoring system for GNSS signals using the FinnRef reference stations of the NLS is left for future work.

This work is divided into six sections: after this introduction the background for GNSS positioning is presented with a detailed view on positioning correction methods available from the NLS positioning service. This section also explains the used data transmission protocols and data format standards. The third section introduces the FinnRef reference station network which is the basis for the NLS positioning service. The service system architecture is briefly presented. After this background information, section four presents different relevant monitoring systems and evaluates their pros and cons. Section five presents the system that was chosen to be used for monitoring of the NLS positioning service. Monitoring results from this system are presented. In section six, conclusions are drawn and future development plans are suggested.

2 Theoretical background

2.1 GNSS positioning

Global Navigation Satellite Systems (GNSS) use satellites in space to provide global three-dimensional positioning of user receivers used on land, on sea, in the air and in space. Satellite-based navigation was first implemented with the US military's Transit system during the 1960s and the Soviet-Russian Tsikada in the 1970s [24]. Shortcomings in these early systems and improvement in technology led the way for development of modern GNSS.

The first and most well-known GNSS is the US *Global Positioning System* GPS which was declared to have initial operational capability in 1993. The Russian Glonass (*Globalnaja navigatsionnaja sputnikovaja sistema*, global navigation satellite system) followed closely, it reached full operational capability in 1996 [24]. More recent systems are the Chinese BeiDou/Compass which does not have global coverage yet, and the European Galileo which started providing initial services in December 2016 [11]. Each of these systems are designed to use 20-30 satellites in medium earth orbits (MEO) to provide global positioning coverage at all times.

Satellite-based positioning is based on the determination of distances between satellites and user receiver. These distances can be deduced by observing signal travel time or phase of the received signal. The first method is used in code range positioning and the latter in phase range positioning. Observed distances between receiver and satellites are combined with known positions of the satellites to compute the three coordinates of the receiver. Solving three unknown coordinates requires three observation equations which means that simultaneous observations to three satellites have to be made. The use of GNSS positioning is based on precise measurement of time in satellite and receiver. GNSS satellites carry precise atomic clocks but receivers usually have inexpensive crystal clocks whose time measurement t_r is not that precise [24, p. 3]. Therefore a fourth observation and observation equation is added to solve the clock error of the receiver. The required positions of the satellites, *ephemerides*, are transmitted to the receiver in the satellite signal's navigation message (broadcast ephemeris) or they can be downloaded from the internet (precise ephemeris).

In code positioning, the distance p between satellite and receiver is determined by observing the travel time τ of the GNSS signal from satellite to receiver and multiplying this time with the speed of light c:

$$p = c\tau. \tag{1}$$

Here τ is the travel time of the signal that can be computed as the difference of signal transmission and reception times (t^s and t_r) according to satellite and receiver clocks, $\tau = t_r(t) - t^s(t-\tau)$, where t is the measurement epoch. However, the observed signal transmission and reception times are not completely errorless as assumed in equation 1. Both clock readings are affected by clock errors $\delta t_r(t)$ and $\delta t^s(t-\tau)$ with respect to system time. So we the introduce the code pseudorange ρ which is the observed, error-affected distance [24][47]

$$\rho = c[t_r(t) + \delta t_r(t) - (t^s(t-\tau) + \delta t^s(t-\tau))]. \tag{2}$$

Rearranging and dropping the explicit reference to the measurement epoch t we get

$$\rho = c\tau + c(\delta t_r - \delta t^s). \tag{3}$$

This code pseudorange has other errors beside clock errors and can then be written as [47, p. 150]

$$\rho_r^s = p_r^s + c(\delta t_r - \delta t^s) + I_r^s + T_r^s + \varepsilon_e^s + \varepsilon_r^s \tag{4}$$

where

ρ_r^s is the observed pseudorange between satellite s and receiver r,

p_r^s is the geometric, true range between satellite s and receiver r, $p_r^s = \sqrt{(X^s - X_r)^2 + (Y^s - Y_r)^2 + (Z^s - Z_r)^2}$. The symbols X, Y and Z with their various sub- and superscripts represent ECEF (Earth-Centered, Earth-Fixed) coordinates of satellite and receiver,

δt_r, δt^s are the receiver and satellite clock error terms,

I_r^s is the distance error term caused by the ionosphere,

T_r^s is the distance error term caused by the troposhere,

ε_e^s is the error caused by errors in the satellite ephemeris for satellite s,

ε_r^s represents the error terms due to unmodeled effects, modeling errors, and measurement errors.

Pseudorange is the observed quantity but naturally the true range p_r^s is the desired one. Precise determination of receiver positions with GNSS requires compensation or elimination of the presented error terms to obtain the best estimate for satellite-receiver distances.

More precise results in GNSS positioning are achieved by using not the code modulated on the carrier wave, but the phase of the carrier itself. The phase of an electromagnetic wave can be measured to better than 0.01 cycles which corresponds to millimeter precision for GNSS signals [24, p. 108]. Positioning using carrier phases is based on the phase difference $\phi(t)$ of the signals received from the satellite and generated in the receiver:

$$\phi(t) = \phi_r(t) - \phi^s(t - \tau) + N \tag{5}$$

where $\phi_r(t)$ is the phase of the signal generated in the receiver, $\phi^s(t-\tau)$ is the phase of the signal received from the satellite, and N is integer ambiguity, the number of full carrier wavelengths between satellite and receiver. In equation 5, the phase angles ϕ are in units of cycles and get values in the interval $[0, 1]$. These could also be expressed in radians in interval $[0, 2\pi]$. Now it is important to note that the phase of the received signal can be related to the phase at the satellite at the time of transmission by the travel time τ of the signal. This, and keeping in mind that phase is frequency f times time, allows us to write

$$\phi^s(t-\tau) = \phi_r(t) - f\tau \tag{6}$$

and substituting this to equation 5 gives

$$\begin{aligned}\phi(t) &= f\tau + N \\ &= \frac{c\tau}{\lambda} + N,\end{aligned} \tag{7}$$

where λ is the signal wavelength. Now equation 7 includes the signal travel time τ which is encumbered by clock errors. As the clock errors are accounted for, the expression becomes

$$\begin{aligned}\phi(t) &= \frac{c\tau}{\lambda} + \frac{c(\delta t_r - \delta t^s)}{\lambda} + N \\ &= \frac{p_r^s}{\lambda} + \frac{c}{\lambda}(\delta t_r - \delta t^s) + N.\end{aligned} \tag{8}$$

This observation equation for carrier phase now relates the observed phase ϕ, the desired range between satellite and receiver p_r^s, carrier wavelength λ, clock errors $\delta t_r, \delta t^s$, and integer ambiguity N. For simplicity, the initial fractional phases of the satellite and receiver signals, ϕ_{s0} and ϕ_{r0}, are included in $\phi(t)$ in this presentation. [47, p. 153][24, p. 107] Observing the carrier phase is practically one measurement of the fractional phase and then just keeping track of changes to the phase [35].

As was the case with code pseudorange, other error terms besides clock errors have to be accounted for in this equation for carrier phase observation:

$$\phi_r^s = \lambda^{-1}[p_r^s - I_r^s + T_r^s] + \frac{c}{\lambda}(\delta t_r - \delta t^s) + N_r^s + \phi_{s0} - \phi_{r0} + \varepsilon_e^s + \varepsilon_r^s \tag{9}$$

where

ϕ_r^s is the observed phase of the carrier signal in cycles,

λ is wavelength of the carrier signal,

p_r^s is the geometric, true range between satellite s and receiver r,

I_r^s is the distance error term caused by the ionosphere. The term has a negative sign since the carrier phase is advanced due to the ionosphere [24, p. 119],

T_r^s is the distance error term caused by the troposhere,

δt_r, δt^s are the receiver and satellite clock error terms,

N_r^s is the integer ambiguity,

ϕ_{s0}, ϕ_{r0} are the observed fractional parts of satellite and receiver signals,

ε_e^s is the error caused by errors in satellite ephemeris for satellite s,

ε_r^s represents the error terms due to unmodeled effects, modeling errors, and measurement errors.

This equation for carrier phase is in units of cycles, it could be multiplied by wavelength λ for metric units. [47, p. 153][59, p. 464] In this text, the notation $\Phi = \lambda\phi$ is used to distinguish between carrier phases in units of metres or cycles.

The position of the GNSS receiver can be solved with a system of minimally four observation equations. This is possible using code observations in equation 4 as the unknown parameters X_r, Y_r, Z_r and δt_r are common for all four equations. But equation 9 for carrier phase observation includes the integer ambiguity N which is an unknown parameter that is specific for each observation. This means that four phase observations introduce a system of equations with four equations and eight unknown parameters. Such a system cannot be solved unambiguously for one epoch [24, p. 254]. As the resolution of integer ambiguities is needed to assess the full accuracy potential of GNSS carrier phase measurements, appropriate solving techniques have been developed [56, p. 269][24, p. 202]. Without a priori information, e.g., of the receiver position, solving of the ambiguities and the equations requires the use of multiple epochs and possibly receivers.

Using observations from one receiver, ambiguities can in theory be resolved if cycle-slip free observations are done for three or more epochs [24, p. 254]. But this would reliably work in practice only if the observation epochs are apart far enough from each other so that the satellite geometry changes. Therefore, positioning with carrier phases is usually done with two or more receivers as *relative positioning*. The use of multiple receivers also helps to improve the results when positioning with code ranges, which is usually known as *differential positioning*. Both of these positioning methods can be performed either with code or carrier phase ranges [24, p. 170-174], but nowadays usually differential positioning is understood as a code based method and relative positioning as a carrier phase based method. Also, both of these methods are possible to practice in post-processing or in real-time mode. In this thesis the focus is on real-time positioning, therefore the following sections will present the theory in this real-time context.

2.1.1 Differential positioning

Differential positioning with code ranges or differential GNSS (DGNSS) is a technique to improve the position determination of a rover receiver by applying corrections provided by GNSS reference stations via datalink. Three different procedures are used for generating the corrections [56, p. 326][24, p. 417]:

1. *Position-domain approach*: Position corrections (ΔX, ΔY, ΔZ or $\Delta\varphi$, $\Delta\lambda$, Δh) are produced by comparing the a priori position of the reference station to the one computed in real time. Rover determines autonomously its position and then applies the provided corrections.

2. *Observation-domain approach*: Pseudoranges observed at the reference station are compared to those which they are expected to be based on the known

positions of the reference station and the satellites. By these differences pseudorange corrections (PRC) and range rate corrections (RRC) are produced and sent to the rover. The rover applies these corrections to the observed pseudoranges and determines its position autonomously.

3. *State-space approach*: The reference station network models the behaviour of various error sources in the area and transmits this information in a so called state vector to the rover. The rover uses this model to estimate the effect of different error sources on the observed distances and determines its position autonomously. The state vector components usually include ephemeris error, satellite clock offsets, ionospheric and tropospheric error parameters.

From these three the observation-domain approach is the one used most commonly. Pseudorange and range rate corrections can be sent in standardized RTCM 2 -format messages 1 and 31, for GPS and Glonass respectively. For the production of corrections one station or a network of stations can be used. Experiments show that static DGNSS measurements in good conditions can achieve an accuracy slightly better than 0.5 meters even when using a single reference station as far as 100 km away [42].

2.1.2 Relative positioning

Relative positioning with carrier phases requires two receivers making simultaneous observations. The aim is to determine the vector between the receivers, meaning that the positions of the receivers are known *relative* to each other. [24, p. 173-174] If the coordinates of one point are known, it can be used as a reference and the coordinates for the other point are solved relative to that.

Relative positioning with two receivers is based on differenced observables, which are formed between observations made at different receivers to different satellites at different epochs. Three cases of differencing are usually considered: single differences, double differences, and triple differences. Differencing removes satellite and receiver residual clock errors, and mitigates ionospheric, tropospheric and orbital errors. [24, p. 174][46]

Single differences are formed from differencing simultaneous observations from two receivers to one satellite. If the receivers A and B are tracking satellite j we can write the single difference of these observations following equation 9

$$\begin{aligned}\phi^j_{AB} &= \phi^j_B - \phi^j_A \\ &= \lambda^{-1}[p^j_{AB} - I^j_{AB} + T^j_{AB}] + f\delta t_{AB} + N^j_{AB} - \phi_{AB0}\end{aligned} \tag{10}$$

where the notation $I^j_{AB} = I^j_B - I^j_A$ is used. The satellite clock bias δt^s and the initial fractional part ϕ_{s0} are cancelled in this equation, and the effect of ionospheric, tropospheric and ephemeris errors are mitigated. The mitigation of errors applies if the receivers are relatively close to each other so that the effect of atmosphere is similar. However, the use of single differences increases the noise level of the observations by a factor of $\sqrt{2}$ compared the original observation [20, p. 355].

Double differences are formed by differencing two single differences where the same two satellites are observed at two receivers A and B. If the observed satellites are j and k the double difference can be written as

$$\begin{aligned}\phi_{AB}^{jk} &= \phi_{AB}^{k} - \phi_{AB}^{j} \\ &= \lambda^{-1}[p_{AB}^{jk} - I_{AB}^{jk} + T_{AB}^{jk}] + N_{AB}^{jk}.\end{aligned} \tag{11}$$

In the double-difference observation also the receiver clock biases are cancelled. Proper handling of integer ambiguities is possible as it is not with single differences. [24, p. 175, 202] The initial fractional phase of the receiver clocks ϕ_{r0} is also removed. Double differencing increases the noise level with a factor of 2 [20, p. 355].

Triple differences are formed by differencing double differences between epochs t_1 and t_2:

$$\phi_{AB}^{jk}(t_{12}) = \lambda^{-1}[p_{AB}^{jk}(t_{12}) - I_{AB}^{jk}(t_{12}) + T_{AB}^{jk}(t_{12})]. \tag{12}$$

Here it is assumed that the integer ambiguities N_{AB}^{jk} remain the same between the epochs (i.e. no cycle slip has occurred) which allows to eliminate them. Triple differences are commonly used for detecting cycle slips in the tracking. Positioning with triple differences is less accurate than with double differences. [47, p. 249]

The relative positioning solution with double-differenced observables is achieved as follows:

1. observations are made simultaneously at receivers A and B
2. double differences ϕ_{AB}^{jk} are computed from the observations
3. double-difference phase ranges p_{AB}^{jk} and ambiguities N_{AB}^{jk} are computed with linear adjustment. Ambiguities are resolved to integer values.

From the linear adjustment, the vector between A and B is solved. If the coordinates of one receiver (e.g., A) are known, three unknowns are removed from the system of equations. This allows to use A as a reference to solve coordinates for rover receiver B. Step 3. is not presented here in detail, the reader can refer for example to [24][47][30][59] for solving of the linear system and [63][49] for two ambiguity resolution methods (LAMBDA and LSAST).

This model for relative phase-range positioning can be applied in post-processing or in real time. Real-time processing is known as the *Real Time Kinematic* (RTK) method, which is widely used in several application fields requiring instantaneous centimeter accuracy. RTK processing is based on the real-time transmission of observations from reference station to rover, resolving of the ambiguities, and computing of the baseline. As it was earlier stated in section 2.1, the linear system with carrier-phase observations cannot be solved in one epoch. Once the integer ambiguities are resolved, the position solution can be computed epoch-by-epoch as long as the tracking of the carrier phase stays continuous, i.e. there are no interruptions or, so called cycle slips. Therefore an important factor in RTK positioning is *time to fix ambiguities* (TTFA) which is the time required to resolve or fix the ambiguities to integer values. If a cycle slip occurs, the number of full carrier waves between receiver and satellite is again unknown and another fixing of the ambiguities is required. If the ambiguities are not fixed, a positioning solution can be achieved but it is a so called float solution where the ambiguities are floating point numbers instead of integers. The accuracy of a float solution ranges from one meter to decimeters, depending on the tracking time, while accuracies of a few centimeters are achieved with fixed ambiguities [56, p. 337][35].

RTK is a truly kinematic method since a solution with fixed ambiguities can be achieved even when the rover is constantly in motion. This is known as *on-the-fly ambiguity resolution* (OTF-AR) [56, p. 294]. Code ranges are commonly used to aid in the kinematic case [24, p. 217][46, p. 246]. OTF resolution of integer ambiguities is usually done in three steps [29][46, p. 245]:

1. computation of float solution with the help of code ranges
2. resolution of the ambiguities to integer values with appropriate methods
3. re-estimation of the parameters of the phase observations with fixed ambiguities.

In step 1. the process uses carrier-phase observations to improve the accuracy of code range observations, and these improved code observations are used to find a better float position solution. The step of improving the code range observations is an important issue in real-time positioning known as *pseudorange smoothing*. Smoothing removes noise from the code observations allowing the estimation of a more accurate search space for the integer ambiguities. The noise removal is due to the use of averaged code pseudoranges R from previous epochs:

$$\rho(t_i)_{\mathrm{sm}} = \frac{1}{n}\sum_{i=1}^{n} R(t_1)_i + \lambda\Delta\phi(t_i, t_1). \tag{13}$$

The change from initial code pseudorange is accurately estimated by the change in carrier phase observation $\Delta\phi(t_i, t_1)$. [24, p. 113] Besides using a moving average, pseudorange smoothing can be done with a Kalman filter [33].

Until now the presented theory has not defined the number of observed frequencies, but as GNSS satellites broadcast on multiple frequencies their advantages should be discussed. Use of multiple frequencies allows to form new observables with linear combinations. Common linear combinations of phase observables are wide-lane ($\mathrm{L_{WL}} = \mathrm{L1}-\mathrm{L2}$), narrow-lane ($\mathrm{L_{NL}} = \mathrm{L1}+\mathrm{L2}$), ionospheric-free ($\mathrm{L_{iono}} = \frac{\mathrm{L_{WL}}+\mathrm{L_{NL}}}{2}$) and extra-wide-lane ($\mathrm{L_{EW}} = \mathrm{L2}-\mathrm{L5}$). These combinations have advantages such as estimating the error in signal propagation caused by the ionosphere and easing the task of ambiguity search. Figure 1 demonstrates the effect of search space size

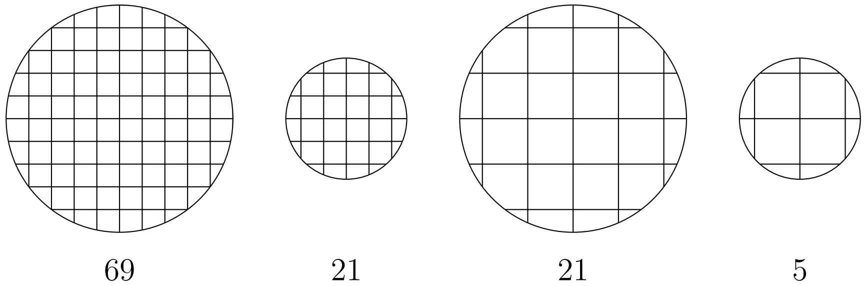

Figure 1: Effect of search space and carrier wavelength on the number of possible ambiguity combinations. Grid spacing represents the used wavelength and circle size the search space uncertainty. The possible satellite-to-receiver distances represented by the grids are not necessarily orthogonal.

and wavelength used on finding the right ambiguity combination for two satellites. Long wavelength (or spacing of the grid) and small uncertainty (or size) of the search space produce clearly less possible ambiguities that should be checked. The benefits of multiple frequencies and combined observations lie in easing the task of ambiguity resolution.

The presented method for RTK positioning using differenced observables is a parameter elimination method, whereas methods that use undifferenced observables are parameter estimation. Both methods use observations from permanent reference stations but only parameter elimination methods actually use relative positioning. [72][56, p. 265] Using a network of reference stations, methods for parameter elimination are the well-known VRS/PRS, MAC and FKP, and for parameter estimation SSR and PPP. Most commercial network RTK providers transmit corrections in a parameter elimination method while parameter estimation methods have not yet been used so broadly [56, p. 269].

2.2 Network RTK methods

Over the last two decades it has been shown that positioning with Network RTK (NRTK) has clear benefits over positioning with traditional RTK using a single reference station. The limitations for single-base RTK are due to distance-dependent biases (orbit error, ionospheric and tropospheric error) that affect the reliable resolution of ambiguities when the distance to the reference station increases. This limitation has led to the use of multiple reference stations in Network RTK, which gives more reliable and homogeneous results with less reference stations than traditional RTK. With a network, the distance-dependent biases can be accurately modelled as the network integer ambiguities are solved using precise reference station coordinates. There exist as many different modelling methods as there are different NRTK software packages. And on top of this, there exist different variations of what information is transmitted to the rover receiver.

In the parameter elimination methods VRS/PRS, MAC and FKP, the information received by the rover includes at least observations from and coordinates of a reference

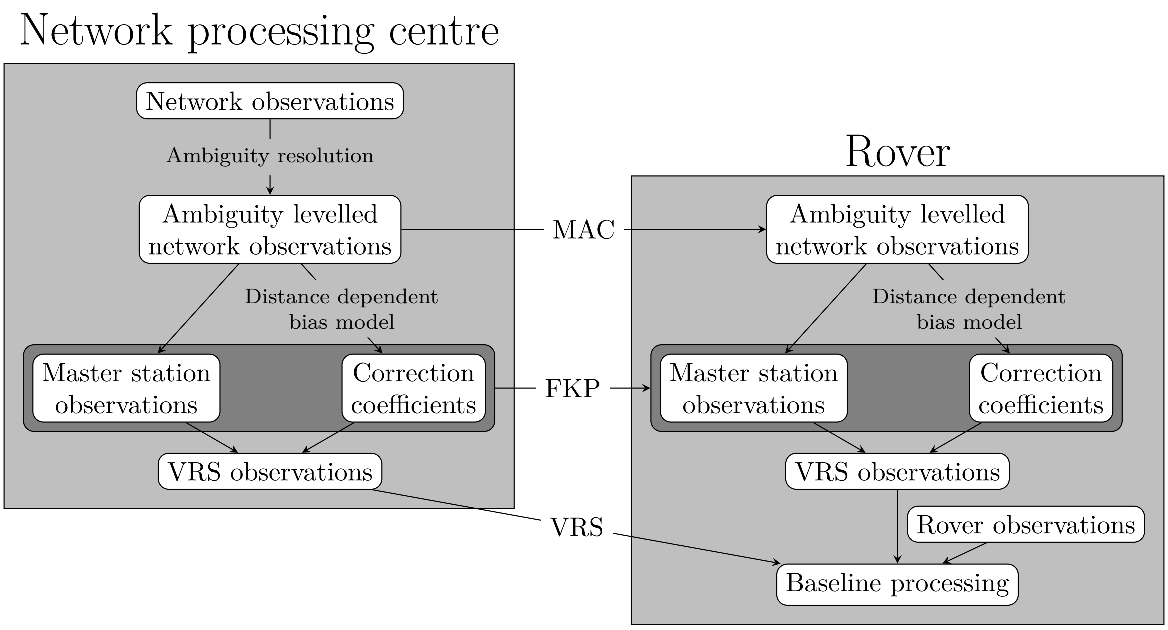

Figure 2: Workflow in different parameter elimination NRTK methods. Modified from [68][60].

station, and usually corrections to the observations. Between these methods there is a difference on where and how the corrections are applied, but eventually the rover positioning result is achieved with single-base RTK. This similarity in the methods is presented with a simplified flowchart in figure 2. The information in the starting point is the same for all methods (network observations), and the result is also the same (baseline processing). The only variety is in whether each processing step is made in the NRTK processing center or in the rover.

The parameter estimation methods SSR and PPP do not use reference station observations in their processing, but instead the whole NRTK modelling or parts of it are used. Therefore the model or corrections need to be transmitted to the rover but no observations. For these methods the workflow of the processing is different from what is presented in figure 2. With SSR or PPP the modelled information based on network observations would be sent straight to the rover and there would be point positioning instead of baseline processing.

The following subsections describe the methods in detail. The basic processing steps and data sent to the rover are explained.

2.2.1 VRS/PRS

The Virtual Reference Station (VRS) concept is based on the creation of virtual observations in the vicinity of the rover. Let us write simplified phase observation equations for a known reference station at location X_{ref} and a virtual reference station at X_{vrs}:

$$\begin{aligned} \phi(X_{\text{ref}}) &= \lambda^{-1}p(X_{\text{ref}}) + N + f(\delta t_r - \delta t^s) \\ \phi(X_{\text{vrs}}) &= \lambda^{-1}p(X_{\text{vrs}}) + N + f(\delta t_r - \delta t^s) \end{aligned} \tag{14}$$

A different location changes only the observed phase ϕ and the true distance to the satellite p. Differencing these two equations leaves

$$\phi(X_{\mathrm{vrs}}) = \phi(X_{\mathrm{ref}}) + \lambda^{-1}[p(X_{\mathrm{vrs}}) - p(X_{\mathrm{ref}})] \tag{15}$$

where everything on the right side is known as the VRS is set to a known location. This is the model for creating observations for VRS based on a true reference station. Residuals from satellite orbit errors, ionospheric and tropospheric refraction are observed at each reference station in the network and modeled so that they are estimated for the VRS location. This error term $\Delta(X_{\mathrm{vrs}})$ is added to the right side of equation 15. [24, p. 189-191]

Positioning with VRS begins with the rover sending its approximate position as an NMEA message to the network RTK provider, where VRS observations are created to this location following equation 15. These observations and the VRS location are transmitted back to the rover which computes a single-base RTK solution as if the VRS was an actual reference station. [34]

Basic advantages of the VRS positioning method are the use of long-existing standards (RTCM, CMR) that are implemented in all major receivers and the use of a simple single baseline RTK solution which is also possible with all receivers. Therefore no complex computation is required at the rover. [28] One disadvantage is that the observations are corrected for each user location individually which disables the possibility to broadcast corrections for an area and requires two-way communication between rover and NRTK provider. As the rover receives the corrected observations right to its position it does not expect distance-dependent errors or see the actual size of these errors so it necessarily does not do modelling of any remaining representation errors. VRS observations are not following standards (RTCM, RINEX) stating that observations should be sent to the user without first applying any corrections [67].

Pseudo reference station (PRS) is a modified concept of VRS where the virtual station is not created in the close proximity of the rover but at a certain distance (for example 5 km). The rover expects distance-dependent errors and so is able to model the remaining representation errors. The sent observations are however corrected for the position sent by the rover. For some RTK rovers the improved positioning algorithms are activated only when the distance to the reference stations is more than few kilometers. [18][71]

2.2.2 FKP

The FKP (German *Flächenkorrekturparameter*, Area Correction Parameters) concept uses a method where the reference station broadcasts its uncorrected observations and a set of gradient parameters used to compute the influence of distance dependent errors on the observations. The rover may use the gradient parameters to estimate the distance dependent errors at its location, correct the received reference station phase ranges and then perform single-base RTK positioning.

The correction parameters are sent as North and East components N_0, E_0 for geometric (non-dispersive) and N_{I}, E_{I} for ionospheric (dispersive) errors. The unit for the gradient components is ppm (parts per million). From the components, distance dependent errors δp_0 for geometric and δp_{I} for ionospheric signals are computed by

$$\begin{aligned} \delta p_0 &= 6.37 \cdot (N_0(\varphi - \varphi_{\mathrm{R}}) + E_0(\lambda - \lambda_{\mathrm{R}}) \cos(\varphi_{\mathrm{R}})) \\ \delta p_{\mathrm{I}} &= 6.37 \cdot H \cdot (N_{\mathrm{I}}(\varphi - \varphi_{\mathrm{R}}) + E_{\mathrm{I}}(\lambda - \lambda_{\mathrm{R}}) \cos(\varphi_{\mathrm{R}})) \end{aligned} \tag{16}$$

where φ,λ and φ_{R},λ_{R} are rover and reference ellipsoidal coordinates and $H = 1 + 16 \cdot (0.53 - \frac{\eta}{\pi})^3$ where η is the elevation angle of the satellite at the rover position. After the interpolation of the errors to the rover position they are combined to generate a correction to the carrier phase measurement on frequency f with

$$\delta p_{\phi,f} = \delta p_0 + \left(\frac{f_1}{f}\right)^2 \delta p_{\mathrm{I}} \tag{17}$$

where f_1 is the L1 frequency. This correction is then applied to the phase range sent by the reference station and single-base RTK positioning is performed. [53, p. 193] The correction parameters in ppm actually define two horizontal planes parallel to the reference ellipsoid around the reference station which are realized with equation 16. This is why FKP is often visualized with two-dimensional planes around the reference stations.

The advantage of the FKP method is that the same parameters defining the correction plane can be broadcast to all the rovers in the area. This leaves also more room for processing in the rover as it can decide how to use the received correction parameters. Besides as a stand-alone technique, FKP can be used in combination with the virtual reference station concept [53, p. 192].

The drawbacks of the FKP method include the need for the rover to perform interpolation of observations and possible inconsistencies at the edge of two adjacent correction planes.

2.2.3 MAC

The MAC (Master-Auxiliary Concept) and MAX (Master-Auxiliary Corrections) concepts use one master and several auxiliary reference stations. The processing center chooses the master and auxiliary stations from the reference station network so that the rover is enclosed within the area, usually with the master station as the closest one. The rover receives coordinates, raw carrier-phase observations, dispersive and non-dispersive corrections for the master station, and for auxiliary stations differences to the master's coordinates and corrections. The rover can use these corrections to model and estimate the errors in its location, correct its own observations and perform single-base RTK positioning with the corrected master station observations. [9] The benefit of sending corrections instead of full observations and coordinates for all stations is the lower use of bandwidth [28].

MAC uses so called ambiguity-levelled observations where raw observations from each reference station in the network are reduced to the same ambiguity level. This reduction is possible as the network ambiguities are resolved due to the modelling or estimation of all error sources in the processing centre [3]. Two reference stations are at common ambiguity level if the integer ambiguities for each phase range have been removed/adjusted so that the integer ambiguities cancel in double differencing [53]. The benefit of the same ambiguity level is that a rover does not have to account for integer ambiguities. The rover may switch between reference stations without having to re-initialize its filter. [28][53]

With MAC corrections the rover can interpret the full information of the used reference station network and independently decide how it will use this information with its own modelling and processing algorithms [9]. Previously presented VRS/PRS and FKP can be completely inferred from MAC data [28], as can be seen in figure 2. However, this requires that the rover knows such algorithms.

As is the case with FKP, MAC can be broadcast to an area that is covered by the master and auxiliary stations. There is no need to individualize the sent corrections to each rover, but it is possible. This variation of MAC where the NRTK service provider computes the corrections directly to the rover's location is known as i-MAX (individualized MAX). It is very similar to VRS, the most important difference being that i-MAX sends actual physical reference station information. [28]

2.2.4 SSR

State Space Representation (SSR) differs from other presented NRTK methods because SSR performs absolute positioning instead of relative. The basic principle in SSR is the determination of each individual error component affecting GNSS measurements at the reference station network and transmitting this information in a state vector to the rover that applies the corrections and performs absolute positioning with undifferenced observables. Carrier-phase observations are physically better represented by undifferenced observables than by double differences [56, p. 266]. This is a key factor in SSR processing. Advantages of undifferenced modeling and ambiguities are: network operation in absolute mode; no correlation in observations; robustness in the network. [71]

The SSR model is presented in a state vector that contains at least the following parameters:

- satellite orbit errors
- satellite clock errors
- satellite signal biases, these are delays of code and carrier phases within the satellite soft- and hardware
- ionospheric delay parameters
- tropospheric delay parameters
- quality indicators for each state parameter.

The rover receiver applies these error parameters to its observations and broadcast ephemerides, and performs absolute positioning. [53, p. 161] Update intervals for state parameters can be much longer than the interval for observations used in relative positioning where the observations have to be transmitted to the rover each epoch. SSR state parameters change more slowly, and the parameters for tropospheric and ionospheric delay can be updated for example every 30 seconds and satellite signal bias only after several minutes. [71]

Already a subset of state vector parameters will result in improved positioning, which allows SSR to be used on different levels. The current state of RTCM standardized SSR messages covers the first three items on the above list which enables the possibility for real-time Precise Point Positioning (PPP) using two observed frequencies. Upcoming second and third stages of standardization for SSR messages are planned to include the parameters for ionospheric and troposheric delay. This would allow so called PPP-RTK where the integer ambiguities are truly dealt with as integers. [53, p. 161-162][71] Augmentation services broadcasting similar correction parameters as in the SSR method do exist, but they are using proprietary data formats and messages. The use of such services requires subscription to the service and a receiver from the same manufacturer supporting the transmitted data. In these global augmentation services the data is sent to the user usually from a geostationary satellite. Major global PPP augmentation services include OmniStar, TerraStar, RTX, StarFix, Veripos, C-Nav, Starfire and Atlas. [12, p. 67]

FKP is described as a simplified mode of SSR, where information about the state of geometric and ionospheric errors is broadcast to the user. But FKP still uses relative positioning whereas true SSR does not. [72] SSR has the same drawback as FKP, a lot of computation is left to be done on the rover.

2.3 GNSS correction data

All of the NRTK methods presented in section 2.2 work by transmitting corrections and possibly observation data from processing center to rover. The transmission is done over a radio link or nowadays usually over the Internet. In order to use the correction data, the rover has to be familiar with the data format and the method for transmission. Therefore standardized data formats and communication protocols are widely used. This section presents the RTCM data format for disseminating real-time GNSS data and the Ntrip protocol for real-time data transmission.

2.3.1 RTCM

The Radio Technical Commission for Maritime Services (RTCM) is an international non-profit scientific, professional and educational organization. RTCM members are organizations both of the government and non-government. RTCM is an independent organization supported by its members from all over the world. RTCM Standards are prepared by Special Committees with different responsibilities. At the moment there are 16 special committees from which number 104, Differential Global Navigation Satellite Systems (DGNSS), is responsible for GNSS standards. [48] In this work, mentions of RTCM always associate to this committee and their standards.

In 1985 RTCM Special Committee 104 suggested a standard for coding and transmitting corrections for differential GNSS used for real-time positioning. The standard defined several message types containing data and information needed for DGPS positioning. Throughout the years and due to the development of GNSS positioning the standard has developed as well to cover RTK methods and use of multiple GNSS. Table 2 shows the version history and important additions from each version. The currently used RTCM versions are 2.3 and 3.3. The first one defines message types primarily for differential positioning and the latter for RTK. Both standards are maintained as current standards because many receivers are designed to use versions 2.x [54].

Table 2: Summarized history of RTCM standard versions and description for important additions. [53, p. 1][56, p. 330][54]

Year	Version	Important additions
1985	1.0	Preliminary version
1990	2.0	PRC, RRC
1994	2.1	Carrier phase data
1998	2.2	Glonass support
2001	2.3	Further refinements, e.g., PCV
2004	3.0	RTK messages, carrier phase data
2009	3.1	NRTK messages, SSR, receiver and antenna description, ephemerides, proprietary messages
2013	3.2	Multiple Signal Messages (MSM), GLO bias, ephemerides
2016	3.3	SBAS, ephemerides

Messages defined in RTMC standards are generally supported by all receiver manufacturers [24, p. 447]. Other formats for real-time transmission of corrections and observations exist, such as Trimble's CMR. However, the RTCM format and Ntrip as a transmission method are closely related as they are standardized by the same commission. Companies and organizations can be assigned proprietary messages for their own experimental use. RTCM message types 4001-4095 are reserved for this.

2.3.2 Ntrip

Ntrip stands for Networked Transmission of RTCM via Internet Protocol which is an application level protocol streaming GNSS data over the Internet. Ntrip is a generic, stateless protocol based on Hypertext Transfer Protocol (HTTP/1.1) and the Real Time Streaming Protocol (RTSP). [52] As a stateless protocol, all Ntrip request messages can be understood in isolation without the server having to have stored any information from previous requests [14]. Ntrip communication usually takes place over HTTP/TCP/IP or RTSP/TCP/IP and RTP/UPD/IP connections.

Ntrip has been designed for disseminating differential correction data or other kinds of GNSS streaming data, including raw data, to stationary or mobile users over the Internet in real time. Many GNSS equipment providers have created their

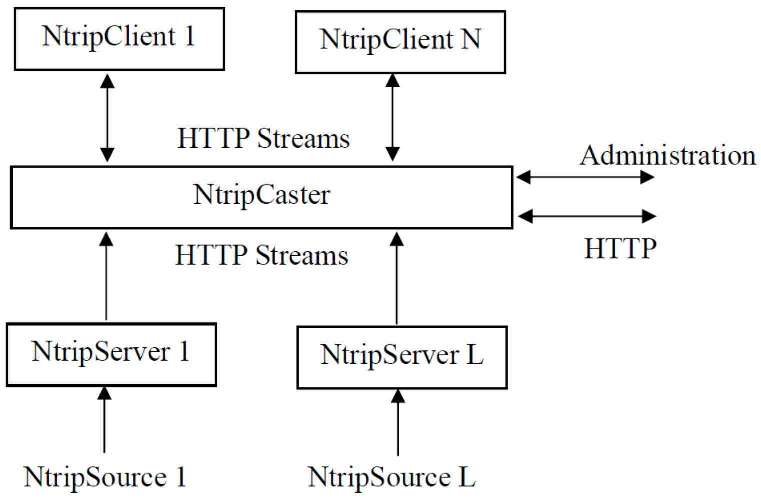

Figure 3: Ntrip system elements. [52]

own data formats for sending raw or correction data, for example receiver binary formats or CMR. All of these formats can be disseminated with Ntrip, but any such use is not to be considered as a part of the Ntrip standard which is closely tied to the RTCM format.

An Ntrip system consists of three different elements: NtripServer, NtripCaster and NtripClient. Figure 3 shows these elements and their relations. NtripServers transfer the data streams generated at NtripSources to NtripCaster which is accessed by NtripClients to receive data streams from desired NtripSources. [52] NtripSource and Server represent a GNSS reference station and NtripClient represents an end user which connects to NtripCaster for correction data. NtripServer's only purpose is to upload data to NtripCaster. [52]

NtripCaster has a more demanding task. All information transmitted is either received or sent by the NtripCaster, which is the center of communication in a Ntrip system [44]. The caster takes care of the following basic tasks: transferring system information to the client, client data request handling, transmission of requested data, handling of errors and wrong requests etc. Note the direction of data flows marked with arrows in figure 3: Servers only upload data to caster, but caster-client communication is two-way. Clients send requests to the caster and also for some network-dependent applications it is necessary to send the position of the client to the caster. This position could be used by the caster to provide a data stream personalized for the user's position (for example VRS/PRS correction stream) or to determine the best data stream to broadcast (closest reference station). This is done by the client sending its position as a NMEA string containing latitude and longitude information. [52]

NtripCaster is controlled by an administrator who organizes all available Ntrip-Sources and defines mountpoints which represent NtripSources. Clients have to choose an NtripSource by its mountpoint, for which a sourcetable exists. The Ntrip-Caster maintains a sourcetable containing information on available NtripSources, networks of sources, and Ntrip Casters. The sourcetable is sent to clients on request. [52] For the end user, the most interesting parts of the sourcetable are the source entries which contain information on the NtripSources represented by mountpoints. Each source has the following information in the sourcetable: Entry type, mountpoint name, identifier/description, data format, format details including message types, carrier or code data, navigation system, source network, country, latitude and longitude, NMEA requirement, single station or network solution, data generator, is data compressed or encrypted, is authentication required, is there a fee, bit rate, and miscellaneous information.

3 FinnRef and the NLS positioning service

3.1 FinnRef

FinnRef is the Finnish Permanent GNSS Network. The original network of 13 GPS stations was built between 1991 and 1996. It was built to provide a basis for the new national reference frame EUREF-FIN, which would be well connected to international reference frames. EUREF-FIN is the Finnish national realization of ETRS89.

The original network was renewed in 2012 and 2013. The network was expanded to consist of 20 GNSS stations across Finland, see figure 4. All stations except two were founded on bedrock. The antennas are set on 3 meter (or 6 m on two stations) steel masts anchored to the bedrock with screw bars. All antennas are Javad choke-ring antennas with SCIGN radomes (JAVRINGANT_DM SCIS). The antennas are individually robot-calibrated by Geo++ to minimize uncertainties in the phase center. The receivers are Javad Delta-G3T (JAVAD TRE_G3TH DELTA) tracking GPS, Glonass, Galileo, Beidou and SBAS.

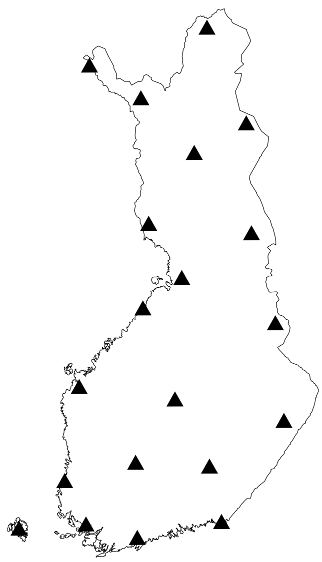

Figure 4: 20 FinnRef stations after the renewal in 2012-2013.

In the 2012-2013 renewal four of the old GPS-only stations (METS, VAAS, JOEN, SODA) were left operational without any changes to the hardware. These stations were left as they were because they all are part of EPN (European Permanent Network) and some are part of the IGS network (International GNSS Service). The rest of the old stations were decommissioned after observations had been gathered in parallel with the old and new receivers for three years. This overlapping data was necessary to guarantee the continuity of the station time series.

In the years 2017-2019 the FinnRef network will be again densified. A total of 20-30 completely new stations will be built in this project. The densification is firstly to improve the NLS NRTK positioning service so that it can be used by NLS surveyors in all measuring activities. Secondly, the densification could allow an active definition of the reference frame, where the national reference frame EUREF-FIN could be completely defined by GNSS stations. A denser network may also allow maintenance of the national height system, and various research activities. [32] These new stations will be built on stable bedrock where reasonably possible. Antennas and their mounting will be the same as in the stations built in 2012-2013, and the receivers will be of type Javad Delta-G3T or Javad Delta-3 (JAVAD TRE_3 DELTA). The first of the new stations has been active from April of 2017 [41]. Appendix A shows a map of old FinnRef stations and new stations that are operational in the end of November 2017 by the time of completion of this thesis.

Data from FinnRef stations is used for:

- creation and maintenance of Finnish coordinate reference frame EUREF-FIN, a national realization of ETRS89. EUREF-FIN is defined by coordinates of 12 FinnRef stations and 100 first order survey marks.
- The European Permanent Network (EPN) [50]. 15 stations' data (four GPS-only) as daily and hourly RINEX-files, and 11 real-time observations streams.
- The International GNSS Service (IGS) network [7]. Three stations' data (one GPS-only).
- The Nordic Geodetic Commission (NKG) GNSS Analysis Centre. 11 stations' data is processed as a sub-network by FGI.
- The Norwegian Mapping Authority Kartverket's ionospheric status monitoring system [31]
- Other scientific research and projects
- The NLS positioning service, see section 3.2.

3.2 The NLS positioning service

The Finnish National Land Survey operates a positioning service that utilizes the data of FinnRef stations to produce GNSS services. These services include real-time correction data streams (DGNSS and RTK) and a RINEX download service. The operation of the NLS positioning service can be explained with figure 5: Observations from all visible GNSS satellites are continuously recorded on FinnRef reference stations. The receivers are connected to the NLS positioning service Input server that receives and stores all data. The Input server transmits the data to the Network processing server which solves the network ambiguities and does error modelling in real time. From there the modelled network information is transferred to the Caster server. The Caster organizes the data in mountpoints and handles the correct transmission of data requested by Ntrip clients, that are the users of the positioning service. In parallel with the Caster works a server called Webservices that deals with other data and communication beside Ntrip. This system can be distributed on multiple servers as is the case for the NLS positioning service, or everything can be run on one server. The benefit of using multiple servers is the smaller workload per server. For example the network processing can put quite a burden on the server and might retard the data flow. Figure 5 presents the functionality of an Ntrip system as depicted in figure 3 but with additional detail and customization for the case of the NLS positioning service.

In the network processing server, all error sources are modelled based on the observations made on the reference stations. Generally put, the caster extracts data from these models for the NtripClient location and sends that data to the client as corrections such as presented in section 2.2. As noted earlier, there are differences in where the modelling results are applied in NRTK processing software and in NRTK service types.

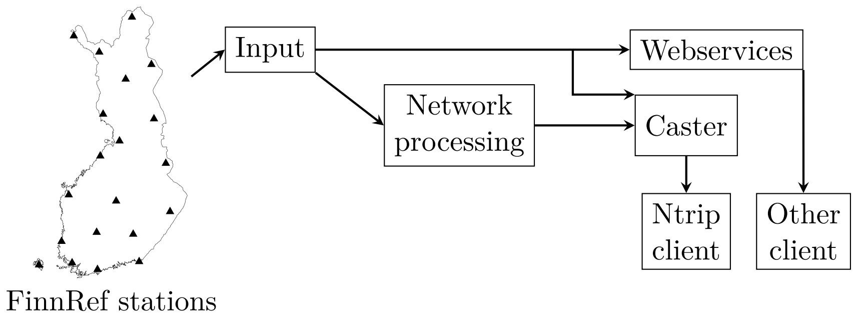

Figure 5: Processing in the NLS positioning service.

The NLS positioning service has been running on Geo++ GNSMART software from year 2013. GNSMART stands for GNSS State Monitoring and Representation Technique, which emphasizes the program's use of state space modelling, where the state of all error components are modelled individually and can be sent to the user at some level. But as the complete state space model can normally not be used by the rover as is, GNSMART can be used to derive different correction types from the state space model. [69] These correction types are for example the DGNSS and NRTK methods presented in section 2.2.

The NLS positioning service currently offers DGNSS corrections as an open service. Corrections are available via internet using the Ntrip protocol in the RTCM 2.x format. Data is available with common login credentials, see instructions on using here [40]. DGNSS corrections are sent as pseudorange and range-rate corrections as RTCM messages 1 and 31. Currently corrections for GPS and Glonass are supported. The open service also includes a RINEX download service where observation data for the last eight weeks from all FinnRef stations is made available. The user can select the observation interval up from 1 second. Use of the RINEX service requires a registration, see instructions here [40]. NRTK corrections and real-time data from the stations is currently not available as open service from the NLS caster. However, temporary licenses for these services can be granted for research or educational purposes. NRTK corrections and observations are sent in RTCM 3.x format.

4 Monitoring of positioning service

In order to provide a real time positioning service at the highest achievable level, the service operators must be aware of how the system is functioning. Monitoring is constant observation of system status. In this work the monitoring of the positioning service covers both the system and its product. These two are tightly related, if the state of the product is not as expected, then this probably applies to the system state as well, and vice versa.

This section describes the issues to be considered in the monitoring of a positioning service. First the concepts related to monitoring are presented, then a review is given of different solutions for monitoring, and finally a summary is presented evaluating the presented solutions and discussion on what approach should be taken in monitoring of the NLS positioning service.

4.1 Aim of monitoring

When considering the monitoring of a positioning system, one should come up with a set of parameters that describe the system and monitor the state of these parameters. [24, p. 268]. When considering a service used for positioning, system functionality could be summarized in one parameter: the achievable positioning accuracy using the service. However, causes for unexpected behaviour are more easily revealed when several parameters are monitored. These parameters should reside in various levels of the positioning service architecture.

In order to have a better understanding of the complete monitoring task, it may be divided into smaller sections. Here the monitoring of the positioning service is divided in four subtasks:

1. stations and receivers
2. network processing
3. correction streams
4. positioning quality.

These four tasks can be located in figure 5 except for the task positioning quality which is completely external from the positioning service system.

Another division of the monitoring task is separation between internal and external monitoring. The software producing network positioning services are complex and include many processes. These actions performed by the software are here denoted as internal monitoring, whereas external monitoring concerns the monitoring of the service's end products as seen by the user. Internal monitoring is mostly automated in the positioning service software, but the operator has to set the acceptance limits and possibly enable monitoring functionalities of the system. Once the limits are properly set the internal monitoring can be quite invisible to the operator if the system is working as intended. But again, in the event of an unwanted incident the set monitoring procedures will prove their worth as the incident cause can be pinpointed. Internal monitoring can also use additional software besides the one producing the service, for example supplementary monitoring of observation data.

External monitoring should be performed outside the positioning service software. At some level it could be done with the producing software but such results might be considered biased if the production system also does product monitoring. If monitoring is performed only in the service software server, situations could rise where the server has connectivity problems and the monitoring system notices this but is not able to send an alarm to the outside as it is affected by the same problem. The system responsible for external monitoring should be compatible with products of any positioning service software. This requirement is easily satisfied if the service products comply with a widely accepted standard.

It should be also considered what information is necessary for a service operator and an end user. As positioning quality with the network service is dependent on various data sources, it is not informative for the end user to know for example the state of each reference station [16]. Instead, the average user would find a set of a few discrete parameters describing the system state more approachable. These parameters could be the current status of a correction stream as an on/off indicator or position deviations of a monitoring receiver. For the service operator, all possible information should be available. The demanding part is to interpret the information and find a set of parameters describing the system state at a sufficient level.

The results of quality control and monitoring are usually given as reports and real-time alarms. Again it is to be decided what level of reporting and alarming is available for the end user. When setting up alarms on the system, the threat of over-alarming has to be considered. An over-alarming system can affect both the operator and the user of a positioning service. Operators tend to ignore a continuous flow of alarms which defeats the purpose, and end users can start to feel less confident in the positioning service if they receive alarms due to errors too often [16, p. 152]. Alarms as warnings for degraded operation for example due to high ionospheric activity have to be separated from error alarms as they are not caused by hardware or software errors. Operators of the service have to carefully consider what alarms are necessary for them and the users. This is not a simple task when the positioning service software can have tens of possible alarms, and not to consider the alarms that can be set from a possible external monitoring system. The thresholds for alarms have to be carefully adjusted to find the level where less harmful events will not raise an alarm. Usually this calls for experience with the system or then the thresholds are sought by trial and error.

Based on this speculation, each of the four monitoring subtasks are next defined more broadly. The following chapters for the four subtasks include a listing of parameters which are essential in monitoring.

Station and receiver monitoring is here considered as details describing the actual operation of a station/receiver and not the state of its observations. This category of monitoring is more related to hardware of the station and its connection to the positioning service server. The following topics are considered as important to be monitored:

- Connection: As the network processing needs observations of the same epoch from all receivers to process the network solution for that epoch, it must wait until all observations are received in the processing server. Should one receiver data have a longer delay than others, the processing of that epoch is delayed or observations are predicted. The reception times of receiver epochs should be monitored in order to define a slow connection or other delays for one receiver or for all. This is done by comparing the epoch observation time stamp to the reception time.
- Receiver clock offset: Time measured by receiver clocks is prone to drift from the appropriate GNSS time frame. The drift is usually corrected in the receiver to keep its time close to the true time. But if something is wrong in the receiver, it could inadvertently be setting false timestamps on observations. [45] This is fortunately noticed in network processing when baselines to a certain receiver deviate too much from the expected.
- Station coordinates: The network processing engine estimates the reference station coordinates for each epoch and compares these to the given coordinates. If the deviation is over a defined threshold, the processing should automatically detect the deviation and take action.
- Station uptime: What percentage of observations has been received from each station in a time frame, e.g., for each week or month. If a certain station has a considerably lower number of received observation epochs, further investigation should be undertaken.
- Receiver board temperature: Like any device with a processor, a receiver cannot operate if the processor temperature rises too high. The receiver will then most probably turn itself off, but if no error message is sent, the reason might remain obscure for the service operator.
- Receiver power: Receiver external power failure can go unnoticed until it runs out of backup battery power if a local backup power source is used. By monitoring the receiver voltage such a situation can be prevented.

Most of these monitoring tasks are mandatory to be done in real time by any network processing engine for it to be functional. The last two are more hardware-related and not mandatory for the operation, but will help the operator in problem solving and so improving the functionality of the service. This list could be expanded with more site-specific details.

Network processing monitoring is here covering also monitoring of the observation data. All GNSS processing algorithms have a fundamental dependence on raw measurements [16]. The network processing software monitors observations epoch by epoch to determine if each set of observations is usable in the network solution. This observation monitoring is a crucial part in the processing as unfit observations can weaken or bias the network solution. The following factors are constantly monitored:

- cycle slips
- carrier-to-noise ratio (CNR)
- observation residuals
- gross range and velocity errors
- age of network solution
- usability of precise ephemeris
- delay between different processes (network processing - caster).

The results of the network processing are the models for each error parameter that can be presented as metric errors of the observation caused by each error source.

Correction streams are the end product of a positioning service. They can be monitored inside or outside the service software. The internal monitoring is done automatically by the service software, where it should be able to notice if a stream process is not operating as expected. However the internal monitoring will not be able to tell if a stream is available from an external network. Therefore the correction streams should be monitored completely independently of the positioning service software.

External mountpoint monitoring is done with an Ntrip client software connecting to the desired mountpoints. There are some possibilities on what parameters are monitored:

- Mountpoint availability: Can a mountpoint be accessed?
- Data availability: If a connection can be made, is data received?
- Data content: If data is received, is it correct? Received messages and their intervals?
- Data age: How long did the data processing and transmission take?

If these parameters are in condition according to the monitoring system, one could expect that the data is reliable for positioning.

Positioning quality monitoring will prove the final performance of a positioning service. This cannot be monitored by any other methods than using the correction data from the positioning service for actual positioning. For this a monitoring receiver on a known fixed position should be used [51]. Monitoring stations act as simulated users of the real time positioning service. A difference with an actual user is that the monitoring stations are usually on good locations with no obstacles and low multipath conditions. [37] When the goal is to monitor the positioning service, the positioning solution should not be affected by factors related to the monitoring station site or degraded observations. By using reasonably good equipment and observing conditions the impact of correction quality is better separated.

When establishing a monitoring station, the location has to be carefully selected. The main factor impacting the selection is the proximity of reference stations, even though with network RTK the distance dependence to the closest reference station should be negligible. But as monitoring is considered, the positioning service appears more credible if the observations for monitoring are gathered farther from the reference stations. With a reference station network as sparse as FinnRef, finding balanced locations for monitoring stations is not a problem. FinnRef stations are built in distant locations away from city centers where less interfering radio communication can be expected. This would allow to build monitoring stations for the NLS positioning service in or near the city centres as there would be no reference stations close by. This would also serve the possible high number of users concentrated in urban areas.

If however the monitoring observations are gathered close to a reference station, precautions against the possibility of similar multipath affecting both stations should be undertaken [51]. If virtual observations are used for monitoring, then multipath or other observation-site conditions need not to be considered. The use of virtual observations for monitoring is later discussed in more detail.

The following parameters are the most important to be monitored [15]:

- initialization time (time to fix ambiguities, TTFA)
- precision (deviation of solutions)
- accuracy (difference to known coordinates).

To monitor the initialization time, the correction data flow to the receiver has to be controlled somehow. The receiver could be set to reset the connections at defined intervals or an external software could be used. This way the monitoring results are short measurement sessions such as a surveyor in the field would perform when using a positioning service. Besides saving the information on the parameters listed, saving of used observations and correction data would assist in problem solving.

4.2 Examples of monitoring systems

Examples in this subsection of monitoring from different countries do not represent the full state of monitoring in each country, but instead the information from the state that is available from their websites or from publications. For some countries the people responsible for their positioning service monitoring were contacted and thus more detailed information was received.

The presented examples are chosen so that different aspects of the monitoring of a real-time positioning service would be well represented. The presented systems are considered external from the software producing the positioning service.

4.2.1 Nordic Geodetic Commission

The NKG (Nordic Geodetic Commission) is an association of geodesists from all Nordic countries. Nowadays also the Baltic states are actively involved in the work mainly conducted in the Working Groups. The NKG Working Group of Positioning and Navigation (2014-2018) has a project "Recommendations for procedures to monitor GNSS positioning services". The project is led by Finland and has members participating from Sweden, Norway, Denmark, Estonia and Latvia. The project aims to find a common view on relevant methods and parameters for the monitoring of GNSS services.

Through this project information on the current monitoring procedures has been exchanged between NKG members from Finland, Sweden, Norway and Estonia. This gained information is referenced here. In the following the relevant (in the scope of this thesis) monitoring procedures from the collaborating countries are presented. The procedures are summarized in table 3. To produce their network RTK service, the public surveying authority in Estonia uses Leica Spider software while in Sweden and Norway Trimble Pivot is used. Besides these service producing softwares the countries operate external software for monitoring of the positioning services. The approximate number of reference stations in their networks are: Norway 200, Sweden over 400, Estonia over 30.

Swedish Lantmäteriet uses Alberding-QC's Checkstream to test their mountpoint availability. It decodes the RTCM stream and checks if correct messages are included in the right intervals, and it has a possibility to produce real-time alarms. More information about Alberding-QC is provided in subsection 4.3.2. Lantmäteriet has a license for testing five mountpoints at a time and the service is run on Alberding servers. In parallel with Alberding-QC they use another software, Ntrip monitor by Harald Gebhard, for testing Ntrip mountpoints.

To monitor the age of outgoing RTCM data from their NRTK service, Lantmäteriet redirects the correction data transmitted via Ntrip into the receivers on monitoring stations back to a program (Imos), that receives the same correction via a locally connected Ntrip client. The program then compares the time in RTCM messages received by these two different routes. With this procedure it can be monitored if there are delays internally in the program producing the positioning service or in the distribution on the Ntrip caster.

For positioning quality monitoring Lantmäteriet has five dedicated monitoring stations over Sweden. The stations are located so that the distance to the closest reference station varies from 10 to 70 km. Four receivers on the monitoring stations are of type Javad Delta and one is of type Trimble NetR9. The antennas are Javad choke-ring type with Dorne Margolin elements (JAVRINGANT_DM) and protective radomes. They are mounted to a building wall or on a chimney.

The monitoring receivers use VRS corrections from Lantmäteriet's network RTK service SWEPOS to calculate the positions. Monitoring receiver control is done with the same software as the data age monitoring, Imos, which is mainly self-developed. RTK processing in the receivers is set to reset every 60 seconds so that each session starts as a single-point solution. The monitoring receivers send the computed position as NMEA messages to the monitoring program which stores all the information to a SQL database and displays the position information online in real time for everyone (available [37]). Lantmäteriet also uses Alberding-QC's RTK-Check for one station's data with VRS corrections, but with RTK-Check the computation is done on a server with RTKlib.

Norwegian Mapping Authority Kartverket has a self-developed program for testing RTCM mountpoints. This program uses the open source-code of the BKG Ntrip client (*Bundesamt für Kartographie und Geodäsie*, available at [5]). This Ntrip client is programmed to connect to each desired mountpoint every minute and check whether it receives data and write this information to a log. The software performs no check on the data content, only if data is available or not. Based on the log files a monthly report of mountpoint uptimes is produced.

Kartverket has eight monitoring stations over Norway, which are organized as four pairs. A monitoring station pair has a common closest reference station, so that one is just some meters away and the other 10-15 km away from the reference station. The closer antenna is typically mounted on the same steel mast as the reference station on a separate ledge, and the farther one to a building wall. All monitoring stations have Topcon NetG3A receivers and Topcon G3-A1 antennas (TPSG3_A1) equipped with TPSD radomes. The LDBV-developed (*Landesamt für Digitalisierung, Breitband und Vermessung*) software RTKMon is used to control the monitoring stations, see subsection 4.3.6 for more information. RTKMon is set to make a periodic connection session every minute to the Ntrip caster of Kartverket's NRTK service CPOS to receive VRS data. Then RTKMon relays the data to monitoring receiver which computes its position and sends the results as NMEA messages back to RTKMon which logs the result of a session to a SQL-database. RTKMon has the possibility to produce alarms if the positioning solution or TTFA is outside specifications.

Estonian Maa-amet monitors their NRTK service ESTPOS mainly with the functions of Leica Spider software which is the service producing software. This software does not have an utility to check ESTPOS mountpoint availability by connecting to the Ntrip caster. Positioning performance monitoring is done with Leica Spider's RTK computation. Using six reference stations, three baselines are constantly computed and compared to the known references. The baseline lengths are less than 30 km.

Table 3: Summary of external monitoring procedures of NRTK services in Sweden, Norway and Estonia.

	Sweden	Norway	Estonia
Stations	5	8 (4 pairs)	0
Receiver	Javad Delta, Trimble NetR9	Topcon NetG3A	-
Antenna	Javad choke-ring	Topcon G3-A1	-
Mountpoint check	yes	yes	no
Software	Alberding QC, IMos/self-developed	RTKMon, BKG Ntrip Client/self-developed	Leica Spider

4.2.2 European Position Determination System

EUPOS (European Position Determination System) is an European non-profit collaboration of public institutions that operate reference station networks and provide GNSS augmentation services. Among other goals, EUPOS aims at ensuring compatibility and interoperability between different NRTK service providers. Members include several Central and Eastern European countries. EUPOS has a few standards for the member states concerning the operation and hardware for NRTK services, such as distance between reference stations, and the use of ETRS89 for reference station coordinates. [27]

An EUPOS working group for NRTK service quality monitoring has been set up with an aim to develop a NRTK quality monitoring tool based on virtual monitoring stations. The tool is to be used for monitoring the positioning services of any EUPOS members. The system has been developed and is maintained by the Geodetic and Cartographic Institute of Slovakia (GKÚ). The working principle is as follows: first an Ntrip client connects to a NRTK service and orders virtual observations (VRS) generated at a predefined location several kilometers off a reference station. Next these VRS observations and physical reference station observations are used to compute a single-base RTK solution to solve for the physical reference station's coordinates. These computed coordinates are then compared to the known coordinates of the reference station and so an estimate of the achievable positioning accuracy using VRS from the service is acquired. RTKlib is used to perform the computation on a server.

The principle has been realized by generating VRS test point regions around reference stations. A total of 24 testing points are created per reference station, at eight different directions and at distances of 2 km, 11 km, and 20 km from the station. In an hour, each point of a region is tested for two minutes and for each hour an average of north, east, and up deviations are computed for each region around a reference station. [57] These monitoring results for each hour of a day are displayed online, see SKPOS and EUPOS [19][10].

The benefit of this implementation is its low cost, as there is no need to set up stations and receivers dedicated only for the monitoring task but instead the data from existing reference station receivers is used. Use of open source RTKlib is also a clear saving instead of purchasing a RTK processing software. The debatable aspect of this method is the use of reference station observations as a rover when that reference station's observations are also used to create the VRS used as a base. The VRS observations are most probably based on the observations of the closest reference station which is now also used as a rover. Smolík and Droščák have tested the method by comparing baselines computed between: 1) VRS - Monitor station and 2) Reference station - Monitor station. For baseline lengths varying from 20 m to 32 km the results give horizontal deviations of about 0.5 cm and 0.5-1.8 cm for the vertical. [58] However this test is a bit different from what is shown in the SKPOS and EUPOS online monitoring tool, where the processed baselines are VRS - Reference station. The option 2) does not use error modelling of the network that is used when VRS observations are created. A comparison between all three mentioned baseline possibilities could show some differences concerning the virtual and physical observations.

As the monitoring system is strongly based on the concept of VRS it cannot be easily used to monitor performance with any other NRTK correction methods. The processing software RTKlib expects observations to a specified location it can use as is, and not raw observations from a reference station with other parameters used to transfer the observations to the desired location (as is the case for example with FKP).

Another example of using virtual observations for monitoring comes from EUPOS member state **Poland**. Nykiel [43] presents a method where VRS data is created at three evenly spaced predefined locations inside a triangle formed by three reference stations in the network. Next RTK baselines are computed between the VRS stations and the results are compared to baselines computed from "true" coordinates of the virtual stations sent with the data. The problem with using VRS data generated by the same network is that the datasets are strongly correlated with each other, which affects independency of the solution. [43] The problem with this method is again the high dependence on VRS data. This method could show if there are inconsistencies in the model that VRS observations are based on if the computed VRS baselines are not what they should be.

The presented solution with virtual observations seems not to be in operational use by Polish authority ASG-EUPOS (*Aktywna Sieć Geodezyjna*, Active Geodetic Network). They are currently employing two GPS-only monitoring stations located more than 20 km away from the closest reference stations. Receivers at the stations are Trimble NetRS and antennas Trimble Zephyr Geodetic TRM41249.00 TZGD. The antennas are mounted on concrete pillars in rural areas with good sky visibility. [22]

Another example of a monitoring system from EUPOS members is **Hungary**'s monitoring tool (available online [21]) that is aimed to the end user as well as for the NRTK service operator. Relevant information for a surveyor using the service is made available in a very simple webpage that can be opened probably at any device.

The webpage shows real-time and history status for: number of tracked satellites on reference stations; availability of correction streams; ionospheric and tropospheric influence on the measurements; summarized skyplot.

4.2.3 EUREF

EUREF operates three EPN Ntrip broadcasters that centralize data distribution from several national Ntrip broadcasters. Real-time observation data from FinnRef stations and other national networks is distributed through their caster www.euref-ip.net that is currently maintained by BKG (*Bundesamt für Kartographie und Geodäsie*). Access to the data streams requires a registration. [6]

BKG operates a monitoring of all data streams provided by their caster [1]. This monitoring does not access the streams via an Ntrip connection, but instead checks internally the log files of the caster to see if data is available [62]. Data on these log files is however written based on the availability of data from national broadcasters, so this BKG monitoring tool does show if data has been accessible from the NLS positioning service caster. BKG monitoring displays only data gaps caused by mountpoint unavailability, no inspection of the data content or age is done. Each mountpoint is accessed and the connection is held until it is disrupted for some reason, and then tried to access for so long that the mountpoint is available again. The disruptions are recorded as outages on log files and graphs.

Data latencies for the real time streams are inspected by EPN and the information for each stream or station is made available on http://epncb.oma.be/. Using an Ntrip client, latencies for all data streams are defined by comparing the time stamp of the received messages with the computer time [4]. These EUREF online services can be used to gain knowledge about the functionality of each raw observation stream mountpoint. The information is good for inspecting the past month or year instead of current real time status as the national broadcasters have no possibility to be alarmed by these monitoring systems. Useful information for national service operators are the outages and latencies of each mountpoint they are providing.

4.2.4 Australia

The RTQC (Real Time Quality Control) system originally developed by Melbourne University researchers can be used as an additional service for reference station network operators and users. RTQC is an external tool for monitoring the quality of raw data from reference stations. NRTK methods are all dependent on the quality of raw measurements, therefore they should be carefully monitored. An instantaneous spike in multipath or an ionospheric disturbance can potentially bias the estimation of integer ambiguities and so impair the accuracy of network modeling. RTCQ is meant to identify irregular patterns and behaviour in satellite observations and tracking data. RTQC is similar to the well-known observation data control quality tool TEQC [8], but for the difference that RTQC works in real time using RTCM observation streams. [16] Another freely available software tool similar to TEQC is G-Nut Anubis developed at Geodetic Observatory Pecný (GOP) [66]. It is intended for qualitative and quantitative monitoring of RINEX data, but a release for quality monitoring of real-time data is under preparation for 2017. This application, G-Nut/QAnubis, was not yet available to be investigated further for this thesis.

Instead of absolute thresholds for alarming, RTQC uses so called relative thresholds where the quality indicators for a certain satellite's signal are compared to the quality indicators for the same signal for past same epochs. This way the compared signals should be as similar as possible that allows easier detection of anomalies in the signal of each epoch. Also, differences between epochs can reveal anomalies for example related to the observation geometry at the sites. For the comparison of the current epoch's data to the past, RTQC must save a database of all observations. The amount of the stored past observations determines the comparison period. The philosophy behind RTQC also includes a fully integrated quality assessment so that only one indicator would be necessary for especially the service users. [16]

RTQC Mobile is developed for evaluating the observations made at the user receiver. RTQC Mobile requires that the user receiver sends its observations to the RTQC service. The service generates an integrated quality indicator based on the user and reference station network's observations. The user rover receives this quality indicator and evaluates how well the overall positioning can be trusted. The quality indicator based on user observations is computed from the recent history of observations instead of a longer period as it is with the reference station quality indicator. [55][17] A rover wanting to use this kind of service has to be able to send its observations to the RTQC service hub and to have the necessary algorithms to take the received quality indicator into account in its positioning computation.

The Australian CRCSI (Cooperative Research Centre for Spatial Information) has been given the RTCM message number 4082 for the purposes of RTQC research. The message is used to transmit the presented quality indicators for reference station data and for the integrated user and CORS data. In the future this message is planned to contain a submessage holding coefficients for a real-time stochastic model that assists in the computation of the rover coordinates. [17]

Also from Australia, Lim et al. have presented a real-time monitoring system for GNSS data quality and integrity [39]. This presented system however focused more on the realization of web-based display of real-time or historic status of reference station observations, their linear combinations, ionospheric delay, data completeness, cycle slips, and integrity parameters. The further development of the system is unclear. However, for monitoring reference station data this kind of a tool could be still useful for example for detection of interference or data outages.

4.3 Software solutions for monitoring

Software solutions presented in this section are examined as to what kind of tools they have for monitoring the produced positioning service. Some of the tools are actually tested while information about others is gathered from available online sources.

4.3.1 Trimble, Leica, Topcon

The three large companies manufacturing GNSS hardware and software, Trimble, Leica and Topcon, have tools for reference station network service monitoring. These monitoring modules are often tightly embedded in their NRTK service software, which limits the possibility to purchase the monitoring modules as independent software. Next are presented some of the tools these companies have for external monitoring.

Trimble Rover Integrity App is their solution for monitoring the positioning performance observed by field users. It is a software module operating on the Trimble Pivot platform which controls dedicated monitoring receivers. The App transmits NRTK correction data to the monitoring receiver and stores the resulting positioning data sent by the receiver. Position deviation from reference coordinates, TTFA, and other relevant statistics are saved and presented by the App. [65] Rover Integrity App is an integrated part in the Trimble Pivot system, so it is not purchasable on its own.

Leica SpiderQC [38] can be purchased as its own software separated from Leica Spider. It has two interesting features:

- Reference Station Integrity Monitoring: SpiderQC can be used to monitor the quality and availability of NRTK corrections by performing real time positioning domain monitoring. Processing can be done in a monitoring receiver or using Spider RT Positioning (real time) on a server where the input is observations and corrections. Statistics such as positioning accuracy, precision, availability and reliability can be used to quantify the integrity of the NRTK service. Alarms can be generated if set thresholds are exceeded.
- Network RTK Performance Monitoring: The Network Online Visualisation of Accuracy (NOVA) feature visualizes the spatial and temporal quality of single base and network RTK positioning over the network. Real time maps show the distribution of residual ionospheric (dispersive) and tropospheric (non-dispersive) errors that can point out troublesome areas in the network. An example of a NOVA map based on Leica's network in Belgium is available online.

Topcon offers monitoring solution embedded within TopNET*live* (IQProxy). There exists a monitoring module that checks if casters and their mountpoints are available. This Ntrip caster monitoring periodically connects via Ntrip to each determined mountpoint and analyzes the data content. Alarming for service operators is possible. As the mountpoint and caster monitoring is inside the NRTK software they can communicate with each other. This enables the possibility for the monitor to send an automatic command to the main software to use a second or backup caster should the original caster instance not be available.

4.3.2 Alberding

Alberding GmbH is a company specialized in development of GNSS software solutions. Their main focus are system solutions for GNSS infrastructure operators. Among their other services Alberding provides a quality control tool dedicated especially for GNSS augmentation service providers. This software package is Alberding-QC and the basic configuration consists of three different software modules, RTK-Check, InspectRTCM, and Checkstream.

The software can be run on a server or it can be purchased to run on an Alberding server. The software is accessible with a web user interface that updates the result tables and graphs in real time. Reports in PDF or CSV formats can be output covering a selected time period.

RTK-Check is a module for positioning domain monitoring. It can be used to control any receiver over TCP/IP connections. RTK-Check connects to an Ntrip caster, transfers the correction via TCP to the receiver, and receives the NMEA output from the receiver via TCP. Such arrangement enables the possibility for RTK-Check to monitor TTFA as it controls the transmission of the correction data. The flow of correction data can be set to be interrupted either after a certain time or after the position has deviated too much from the given reference coordinates. Based on these positioning sessions RTK-Check saves and plots statistics for example of coordinate deviations, HDOP, number of fixed satellites, age of the correction data, connection time to the receiver, TTFA, and solution state. The saved value of the parameters saved for each session is averaged from the received NMEA messages of that session. Table 4 shows an example of the session data from RTK-Check. Three RTK sessions are displayed, session length is 120 s with 30 s intervals between the sessions. Column "Epochs" tells how many epochs of a session were of the solution quality shown in column "Solution". Good additional information would be standard deviations of the session data to get a better insight into the uncertainty of each session.

All session data from a selected time window can be exported from RTK-Check to CSV or PDF format. The PDF report includes the session data as a table and graphs for all mentioned parameters. Sending real time alarms is also possible. For each monitoring solution email and SMS alarms can be sent if parameter values are over set thresholds for a certain time. SMS alarming requires a subscription from an operator, email alarms use Alberding server.

Table 4: Tabular session data content of Alberding-QC's RTK-Check. Values for position deviations are in centimeters and for TTFA and Age in seconds.

Time	Solution	Epochs	ΔN	ΔE	ΔH	ΔNE	TTFA	Sat.	HDOP	Age	Checktype	Delay
08:58:17	RTK Fixed	108/120	-0.6	0.5	13.5	0.8	4	19	0.6	-	Interval Check	5
08:55:47	RTK Fixed	113/120	-0.2	0.6	12.6	0.6	4	19	0.6	-	Interval Check	5
08:53:16	RTK Fixed	113/120	-0.5	0.5	13.4	0.7	3	18	0.5	-	Interval Check	6
08:50:46	RTK Fixed	114/120	-0.3	0.2	13.2	0.4	3	19	0.5	-	Interval Check	4
08:48:15	RTK Fixed	112/120	-0.8	0.1	12.3	0.8	3	19	0.6	-	Interval Check	4

RTK-Check can be used to monitor any solution state defined by the NMEA GGA message's data field fix quality indicator. The states commonly achieved are: 1 = single solution; 2 = differential solution; 4 = RTK with fixed ambiguities; 5 = RTK with float ambiguities. As the operation of RTK-Check is based on the received NMEA messages, it can be operated with only giving an NMEA input. This way any NMEA input can be visualized with RTK-Check as averages of some short session, e.g., the input could be suspended for 1 s for every 60 seconds.

Besides controlling a physical or any external receiver, RTK-Check has an embedded RTKlib computation. It operates in the same way as any receiver, except that the computation is done on a server with RTKlib. The RTKlib configuration file can be fully modified. [23]

Checkstream is a module for monitoring Ntrip mountpoints. It performs periodical connections to selected Ntrip mountpoints, checks the data, and writes statistics. The connection time and the wait time before a new connection are freely set. Checkstream performs a check on the received data content according to a user defined control string that is given as expected message types and their input intervals. An RTCM observation stream could be checked against string "$1006(n), 1008(n), 1077(1), 1087(1), 1097(1)$". This means that messages 1077-1097 should be received with 1 second interval. For 1006 and 1008 the interval is not defined, so no action is taken if they are not included in the sample. In this example, if the average interval for messages 1077-1097 is outside set limits (e.g., 0.8 to 1.2 seconds) or they are completely missing, Checkstream will generate an alarm. Definable alarm types and their explanations are listed in table 5. If no alarm condition is fulfilled, an "OK" status is written in the statistics. Email and SMS alarming can be defined. [23][26]

Table 5: Alberding-QC Checkstream errors and corresponding alarms with explanations.

Error / Alarm	Explanation
Connection	Connection to the stream is not possible
Login	Access to the caster was denied
NMEA	NMEA string is missing or wrong
Message	No data received, data or data rate is wrong or unreadable
Nullframe	Problem with the software providing data for the caster
High Data Age	Average data delay is too high

RTCM 2.x, RTCM 3.x, CMR and CMR+ data streams can be decoded which allows the use of all defined alarms. Other data formats transmitted via Ntrip can be monitored with Checkstream but the only checks made are that the data format is right and that data is received. [26] Checkstream reports from a selected time period can be exported to a PDF file. An example of such a report is given in Appendix B.

InspectRTCM is a module for inspecting and decoding RTCM and CMR data streams in real time. It has two functions, either decode and display data or define rates for message types in the streams. For the first option, InspectRTCM opens a connection to a stream and displays the decoded data on screen. A file containing RTCM or CMR can also be used as input. The decoded data can then be downloaded. The data rate inspection connects to the data stream and by comparing the times of received messages it defines average transmission intervals. Example output for a RTCM 1077 message is:

$$1077(1.0 * 137 + 2.0 * 4 = 1.0 * 141)\ \text{time=}145.6 \rightarrow 1077(1)$$

Alberding has another software package besides Alberding-QC, Alberding GNSS Status Software. That is however more focused on the quality assessment of GNSS reference stations instead of external positioning service performance monitoring. Status Software could do continuous monitoring of reference or monitoring stations but not to monitor TTFA and the effect of re-initialization. So the possibilities to simulate a rover user in the field are more limited. Repetitive Ntrip connections as with Alberding-QC Checkstream are also not possible with the Status Software.

4.3.3 Geo++

Geo++ has several software modules that can be used to perform monitoring separate from the GNSMART software producing the network corrections. All of the following modules or software packages were tested in this work.

GNALERT_LITE is a module for controlling alarms sent by all GNSMART modules active on the server. Most of the modules are capable of generating alarms on various conditions which makes GNSMART alarming possibilities versatile. The complete list of possible alarms with their explanations and alarming modules is given in Appendix C [18]. There exists a small command line program *sendalarm.exe* that can be called by non-Geo++ software to send alarms for GNALERT_LITE, which allows centralizing the alarms of different software on the server.

GNNET-RTK Monitoring and GNRT-K are Geo++ software packages containing tools for positioning quality monitoring. GNNET-RTK Monitoring takes advantage of several input reference stations to compute the optimal positioning solution for a rover receiver in the network using Geo++ algorithms. As it is not using a correction stream from a positioning service (e.g., FKP or VRS), it is not suitable for monitoring the performance using such a service. Instead, it is more intended for example for continuous deformation monitoring of a structure using a fixed rover antenna. GNRT-K however, is a rover positioning module that acts as any physical receiver. It inputs observations from a receiver and correction data (DGNSS or RTK) and outputs a real time positioning solution. GNRT-K does not have ready utilities for re-initialization of the Ntrip correction stream and TTFA monitoring so it would require an additional control system for positioning service performance monitoring.

Mountpoint testing can be performed with data input modules RTCM_IN and RTCMR_IN, of which the first one is for RTCM 3.x and the latter for RTCM 2.x data. There is no actual Geo++ software package that would utilize these for Ntrip mountpoint monitoring, but it is easily configurable in a batch file. This has been tested by writing a batch file which periodically calls a RTCMR_IN process that connects to an Ntrip mountpoint for a certain time (60 seconds), records the number of each received RTCM message type, shuts down the process, waits for 30 seconds, and then starts over. In this test the number of received RTCM messages is saved to a log file. These log files can then be used to extract statistical information about each monitored mountpoint. The RTCM_IN and RTCMR_IN modules can be set to send email alarms if a mountpoint is not accessible or no data is received.

GNCIM (Communication Integrity Monitoring) realizes a monitoring of RTCM communication locally on the reference station, or on the server running the service. This is done by comparing the RTCM signal sent by the caster to the one received by the client. With GNCIM caster and client can be on the same server (or receiver), or on different servers but then the output signal has to be transmitted to the receiving server with an additional communication line. Data age, amount and content of the signals are compared and missing, delayed or wrong RTCM messages are detected. GNCIM can write statistics on the communication and send alarms. [18] GNSMART alarms triggered by GNCIM are Alarm-IDs 3001-3004 in Appendix C. Alarms 3002 and 3003 however require that the RTCM communication is done over radio transmission and the signal strength is observed with an additional sensor.

GNRIM (RTCM Integrity Monitoring) monitors RTCM correction data by comparing the data of at least two reference stations. The RTCM monitoring is normally done by either looking at individual corrections of each satellite observed on a reference station absolutely or by statistically comparing these with the corrections for the same satellite on one or more other reference stations. Residuals are computed from the comparison of different input sources, corrections are the absolute values. [18] Alarms and monitored parameters supported by GNRIM are Alarm-IDs 1001-1013 in Appendix C listing GNSMART alarms.

4.3.4 FGI-GSRx

FGI-GSRx is a software-defined GNSS receiver developed by the Finnish Geospatial Research Institute FGI which is a part of the NLS. It is capable of processing the following signals: GPS L1, Glonass L1, Galileo E1, BeiDou B1 and IRNSS signals. The receiver is written completely in MATLAB and is intended mainly for post-processing. [25] For this thesis the current capabilities of FGI-GSRx in 2017 were inquired from the responsible researchers. Besides single-point positioning, the receiver can now perform GPS L1 RTK and use SSR RTCM messages for GPS L1 point positioning.

The greatest benefit of using an in-house developed software receiver would be the complete knowledge of what is happening in the software. Another benefit would be the savings made when there would be no need to purchase commercial RTK processing software licenses. An actual front-end antenna would naturally be necessary but one antenna's observations could be processed in real time with an infinite number of parallel instances of FGI-GSRx. Use of in-house developed software would however require constant maintenance and development if it was to be used for operational monitoring. Cost analysis for buying software or developing and maintaining is yet another question. However, it would be excellent publicity within the scientific community and society at large to use such sophisticated in-house developed tools for operational monitoring. For these reasons the use of FGI-GSRx in the NLS positioning service monitoring was considered and presented in this work.

4.3.5 RTKlib

RTKlib is an open source software package for GNSS data handling, and RTK and PPP processing. Features relevant for monitoring of real time positioning service are RTKlib's real time positioning module rtknavi/rtkrcv and the module strsvr/str2str used for data stream communication. The former ones (rtknavi and strsvr) are run with a graphical user interface (Virtual Component Library, VCL) while the latter ones are called from the command line. [61]

strsvr/str2str are presented here from the wide variety of free Ntrip clients available online. Besides receiving data via Ntrip, some of these clients are able to decode, transmit and transfer the data. These clients would require additional development work to make them beneficial for Ntrip mountpoint monitoring, as they usually lack alarming functions and a possibility for periodical connections.

rtknavi/rtkrcv could be a powerful tool for RTK positioning considering it is open source software. It could be well used acting as a monitoring receiver to perform positioning domain monitoring by using observations from a monitoring receiver and a correction stream. One issue with open source software is the lack of certainty for the continuity of quality software development.

4.3.6 RTKMon

RTKMon is a software developed and maintained by LDBV Bayern which is the local surveying authority in German Bavaria. RTKMon is used to monitor the positioning performance achieved by using an NRTK correction stream. For this RTKMon initializes positioning sessions where it first connects to an Ntrip caster for corrections, then transmits the data to a monitoring receiver which computes the positioning solution and transmits it as a NMEA message back to RTKMon. As the predefined session time ends, RTKMon ends the connection to the caster and so the receiver does not get any corrections and falls back to autonomous positioning. The information of a session is saved to a database and after the predefined timeout, RTKMon starts a new session. The received NMEA messages are summarized to session information that is saved to the SQL database. Position solution and other relevant parameters from a session are averaged from the NMEA messages, and one row of data is saved to the database for a session. The program can send email alarms if some of the monitored parameters exceed the set tolerance.

RTKMon can be used to perform monitoring of different positioning solution states; RTK with fixed or float ambiguities, DGNSS, or autonomous positioning. Recording of a session starts when the selected solution state is achieved. The software cannot perform monitoring of these states simultaneously. This means that if RTKMon is set to do RTK monitoring with fixed ambiguities and no such a solution is achieved in a positioning session, it will be saved as missing. This can result in gaps in the session data if the monitored solution state is not achieved in a session. But if necessary, the positioning data of this non-fixed session can be manually extracted from the saved NMEA message logs. [15]

RTKMon is run as a Windows Service (program operating in the background) and it is controlled with a configuration file. The program has a GUI which is only for plotting of the session data, and a web interface for the same purpose. The web display is used by SAPOS Bayern, their monitoring station information is available here [2].

SAPOS is the satellite positioning service of the German National Survey (AdV, *Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland*). SAPOS consists of 16 agencies (German states) that each operate a separate network of reference stations and the related positioning service. The number of reference stations on the territory of each state varies between 1 to 37, the median is 16 stations. The states also operate a number of monitoring stations that use a NRTK correction stream from the service. Information about the number of monitoring stations is available only for six states, from which all had 2-3 monitoring stations. RTKMon is used for the monitoring station control in multiple states.

Information about the equipment on these monitoring stations is available for only two states (six stations). Used receivers include a few reference receivers (Trimble NetR5, Septentrio Polar X5) and a few RTK rover receivers (Leica GS10, Leica GX1230). Antennas used are mostly RTK rover antennas (e.g. Leica AS10, navXperienec 3G+C) but also one choke ring antenna is used (SEPCHOKE_B3E6). Most of the monitoring stations are mounted on buildings in urban areas.

4.4 Summary

Several tools usable in monitoring of a real time positioning service were presented. Returning to the four monitoring subtasks presented in section 4.1 it is clear that real time monitoring of subtasks 1. and 2. is mainly the responsibility of the service producing software. Solutions such as the Australians' RTQC do exist for reference station observation monitoring but much of this is already done by the network software. A tool for monitoring and visualizing the observations in real time would be useful for a network operator to spot problems at a glance.

Subtasks 3. and 4. dealing with correction streams and achievable positioning quality monitoring can be implemented with many of the presented tools. Some variety exists in the implementation of how monitoring stations are used in different countries. Figure 6 presents a summarizing sketch for the uses of virtual and physical

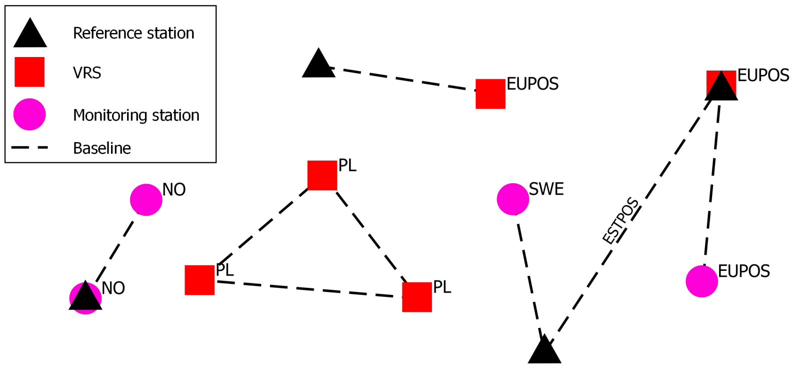

Figure 6: Use of physical and virtual stations in presented monitoring schemes.

monitoring stations. In most cases the used NRTK method is VRS, but for simplicity these baselines are drawn to the closest reference station.

Use of virtual observations for monitoring relies on the assumption that VRS is the main method for positioning with services using permanent reference stations. If the focus moves to network methods where virtual observations are not used (i.e. parameter estimation methods), then monitoring systems dependent on them become somewhat obsolete. Therefore a more consistent solution is to monitor the achievable positioning quality with an actual monitoring station and receiver, that in theory can be utilized to use any GNSS augmentation method. Precise real time positioning is probably not changing from the concept of a receiver using its observations and some external correction. The hardware on a monitoring station is less demanding to change than the whole concept of the monitoring system.

The Norwegian method to use two physical monitoring stations is interesting but it does require resources. The use of existing infrastructure on the monitored reference station however lowers the cost to include only the acquisition of antenna and receiver. A similar system could be implemented with FinnRef stations by using the four old GPS-only stations METS, VAAS, JOEN and SODA located on the same sites as current stations, with distances between the antennas only some tens of meters. But as the old receivers are used as reference stations for EPN they cannot perform rover computation, but their observation data can be made available. With software processing, these stations could be used for monitoring in the vicinity of reference stations.

Besides the use of monitoring stations, software solutions for monitoring were inspected. Ready software solutions for NRTK service monitoring are not very common, or they are embedded in the reference station network software, as is the case for Trimble and Topcon. Several possibilities for Ntrip clients and RTK/DGNSS computation exist, but such tools lack the possibilities to perform real time monitoring tasks. Most of the tools would need an external control software to make them usable. Table 6 summarizes the possibilities of the available commercial or other software for Ntrip mountpoint and positioning quality monitoring. Some national NRTK service providers have developed their own software solutions for dealing with these basic external monitoring tasks.

Table 6: Summary of available software possibilities for external monitoring.

	Correction streams	Positioning quality	
		Receiver control	Computation
Trimble		x	
Leica		x	x
Topcon	x		
Alberding	x	x	x
Geo++		x	x
FGI-GSRx			x
RTKlib	x		x
RTKMon		x	

5 Applied improvement procedures for the monitoring of the NLS positioning service

Based on the different monitoring possibilities evaluated in section 4 and the needs of the NLS, the following actions to improve monitoring of the NLS positioning service were taken:

1. more GNSMART features enabled
2. procurement of Alberding-QC and Geo++ GNRT-K
3. use of physical monitoring receivers or data.

The GNSMART software producing the NLS positioning service has been used in the NLS mainly in research projects, and not for continuous operative measurement activities. The open DGNSS service has been offered without any guarantee, but as a best-effort delivery. Therefore many small features available in GNSMART have not been utilized. Now as the monitoring possibilities of the software have been further investigated for this work, more monitoring features of GNSMART have been enabled. These features are categorized here as internal monitoring and are presented more in subsection 5.1.

The second improvement point in the above list concerns external monitoring. As the initial monitoring assembly was nonexistent anything would be an improvement. Development of in-house software exploiting available open-source tools was considered, but this was deemed too time-consuming and challenging as in-house software would require constant maintenance and updating. Therefore after evaluating available possibilities, the use of commercial software was perceived to be a viable solution. It was also noted that the monitoring solution would be practical if it were concentrated to be accessed from a single user interface. These observations led to the purchase of the Alberding-QC software package used for monitoring mountpoint status and controlling monitoring receivers. The software is being run on Alberding servers and the user interface is accessed with a browser. As the monitoring is done completely separated from NLS servers and network it is truly an external monitoring system. Use and results of Alberding-QC mountpoint and positioning quality monitoring are presented in detail in subsection 5.2. To work alongside Alberding QC, the Geo++ rover computation software package GNRT-K was purchased.

During this thesis, no permanent physical monitoring stations for positioning quality monitoring were built. Instead observation data from different available sources was used to verify the functionality and suitability of the established monitoring procedures. These data sources were: one Javad receiver located on the roof of the FGI building in Kirkkonummi; SWEPOS stations (see [36]); four old FinnRef stations active in EPN; active FinnRef stations. The use of data from commercial operators' stations will also be considered later. But as these are only sources of data, the receivers themselves cannot be used to perform the positioning computation. This is where GNRT-K is used, to perform the actual rover positioning using observations from the mentioned sources with a correction stream from the

NLS positioning service. Besides GNRT-K also RTKlib is used for the positioning computation. Details of this arrangement are presented in subsection 5.2.

This solution using data from different external sources is not however deemed as the optimal one. If the monitoring stations are not owned by the NLS there is no right to decide on the equipment and more importantly, no guarantee on the continuity of a certain station. Therefore the building of NLS owned, dedicated monitoring stations is recommended. Plans for the stations and other development for monitoring procedures are presented in subsection 5.3.

5.1 Internal monitoring

As the positioning service software GNSMART does continuous monitoring of all parameters, the task for improving the inner monitoring is mainly setting up relevant alarms in the software. Set alarms sorted by their ID are listed in table 7.

Table 7: Enabled GNSMART alarms.

Alarm-ID	Function
2005	Receiver raw data timeout
2006	Receiver power low (less than 10 V)
2007	Receiver board temperature high (over 65 °C)
2008	RINEX storage failure
3005	Receiver data timeout
3006	No FKP available for this station
3009	Precise ephemeris timeout
3013	High delay of observation data
3017	High network irregularity

Alarms 2005 and 3005 monitor the flow of data from reference stations to the software at two different steps of the process, in the data receiving module and after that in the processing module. Alarm 3013 monitors the age of data received in Input (see figure 5) and again in Caster. This monitoring procedure shows possible data delays between reference stations and input server, and between input and caster. Alarms 2006 and 2007 are focused on detection of harmful effects in receiver hardware. Alarm 2008 for RINEX storage failure tells on the failure of storing RINEX data from the receiver input process. This can detect for example changes in the file system that have not been notified in the startup of the processing software. Alarms 3006 and 3009 monitor the basic functionality of the network processing. If no FKP is available it means that the number of satellites from that station used for the network solution is too low. 3009 monitors the availability of precise ephemeris. Alarm 3017 monitors the ionospheric irregularities detected in the network computation and can tell the operator if problems for example with ambiguity fixing can be expected.

Alarms are managed by the GNSMART alarming module GNALERT_LITE presented in subsection 4.3.3. Alarming thresholds have been tentatively adjusted so alerting only occurs in meaningful situations. Some of the enabled alarms have a slight redundancy, e.g., the 2005 and 3005 alarms are for the same issue but at different steps of the process. Alarming for such process chains have been minimized but some of the alarms are important to gain a better insight into the problem. Email messages are sent to operators by a separate software, and its correct operation is monitored simply by sending an email once a day.

The RTCM standard defines an indicator for reference station health status that is sent in the header part of each message. The indicator has eight different states: 0-5 define User Differential Range Error (UDRE); 6 indicates that the reference station transmission is not monitored; 7 indicates that the reference station is not working. The state for this indicator is obtained by using a Reference Station Integrity Monitor station (RSIM) that receives differential GNSS corrections from a reference station and monitors their usability on positioning. This would require special two-way communication between the stations by using RSIM messages defined in the RTCM standard for DGPS and reference stations and integrity monitors. GNSMART has the possibility to force the indicator state to be set to “monitored”, but this is not applied as the monitoring is not done following the definitions in the standards. All DGNSS messages from the NLS positioning service are therefore sent with the health/monitored indicator being 6, not monitored. The indicator however applies only for RTCM 2.x messages, for RTCM 3.x messages the field is not used and is always set to 1. [53][51]

5.2 External monitoring

External monitoring covering mountpoint testing and positioning monitoring has been implemented with Alberding-QC. The current purchased license allows to monitor simultaneously five mountpoints and two positioning computations, but the permissions can be easily expanded.

In Alberding-QC Checkstream, monitored mountpoints are set so that mountpoints from each caster instance (port) in the NLS positioning service are checked. This way possible connection errors in all caster instances are detected. One of the monitored streams is a RTCM 3 observation stream from a FinnRef station, the rest are DGNSS or NRTK correction streams. The generation of station observation streams in GNSMART is different from correction streams as no network processing is applied. The arrow in figure 5 straight from Input to Caster represents these observation streams. Monitoring streams with and without network processing applied can reveal for example latency caused by the processing. The four monitored correction streams require NMEA locations from Alberding-QC, which are set in different parts of Finland.

The length of a connection session in mountpoint monitoring is freely selectable. Now the five connections are set with varying starting intervals and connection lengths. They are timed so that theoretically at every moment one connection to the caster is active from Alberding-QC. The connection lengths vary from 25 to 30 seconds. Short connection sessions are better suited for detecting too long intervals between received messages as possible missing messages are not smoothed in averaging of a long session. This arrangement results on average in 2705 initialized connections to each mountpoint in a day. The data content of a connection session is compared to the control string defined for each mountpoint as described in subsection 4.3.2. From the alarms in table 5 alarms for connection, message and data age errors are set to send email alerts for the NLS positioning service operators, other alarming conditions are checked from the Alberding-QC user interface.

Positioning domain monitoring is controlled with Alberding-QC's RTK-Check that performs periodical RTK-sessions. The length of the sessions is set to 120 seconds with a 30 second timeout before beginning a new session. This length is chosen since on most occasions the ambiguities can be fixed to integer values in this time and again a too long session would result in too much averaging. Also, if it were a surveyor in the field, he/she would not wait more than 2 minutes before re-initializing the filter in hopes of fixing.

Figure 7 shows the functionality of Alberding-QC with GNRT-K. Alberding receives corrections from the NLS positioning service via Ntrip, transmits these to a monitoring receiver which returns positioning results as a NMEA GGA message which Alberding visualizes and stores into the database. In figure 7 the block Receiver is any source for observation data for block GNRT-K, and these two blocks could be replaced by one receiver block doing both the front-end observing and the positioning computation. GNRT-K is run on its own NLS server separate from the NLS positioning service. This server is dedicated to be used for monitoring purposes only.

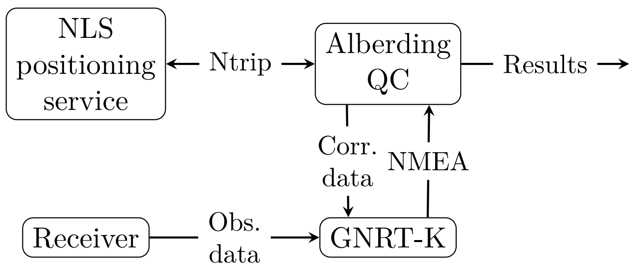

Figure 7: Monitoring scheme using Alberding-QC and GNRT-K with observation data.

This setup for Alberding has been tested using GNRT-K and RTKlib with various sources for observations. SWEPOS stations (see [36]) near the border in Lapland that have been used are: Övertorneå (45 km to TORN), Haparanda (30 km to TORN), Junosuando (79 km to OLOS, 73 km to KOL2) and Korpilombolo (65 km to KOL2). From the mentioned receivers, results extracted from Alberding-QC for Haparanda are presented. Observations at Haparanda station are made with a JAVAD TRE_G3T receiver and a JAVRINGANT_DM antenna located on the roof of Haparanda railway station with excellent sky visibility. The used stream from the NLS positioning service is PRS. This mountpoint creates a pseudo reference station 4.31 km away from the position sent by the rover. The used format for PRS and rover (Haparanda) observations is RTCM 3.2 MSM7 high precision messages 1077 and 1087, for GPS and Glonass.

Figures 8 and 9 display the results for 18 hours of 120 second sessions. The images are extracted from the Alberding-QC user interface. Session information is also given as a summary table, this information is extracted to table 8. A fix solution was achieved in all displayed sessions. The few clear deviations from the reference position are most probably wrong fixes as they deviate by tens of centimeters. The constant circa 10 cm deviation in the height component is due to using coordinates of the marker as reference in this test instead of the antenna phase center.

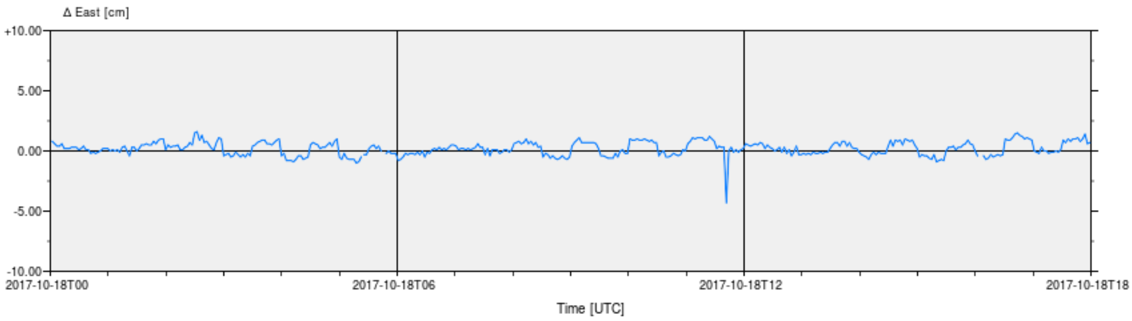

Figure 8: Positioning monitoring results from Alberding-QC for SWEPOS station Haparanda. Deviation of east coordinate for 428 observation sessions of 120 seconds each.

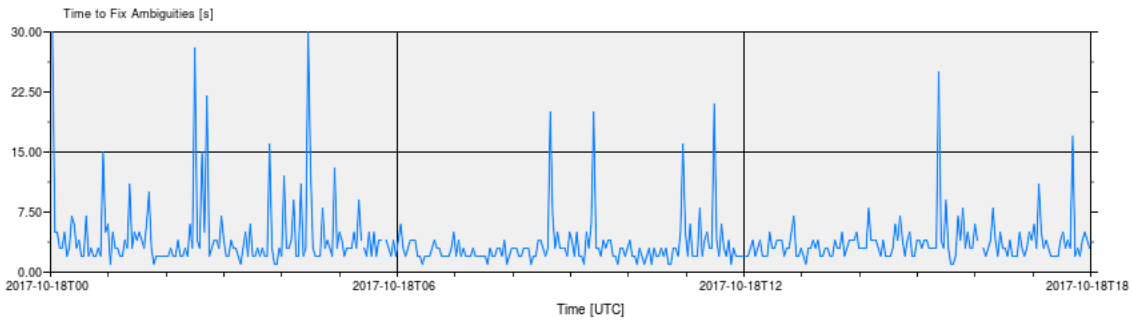

Figure 9: Positioning monitoring results from Alberding-QC for SWEPOS station Haparanda. TTFA for 428 observation sessions of 120 seconds each.

Table 8: Positioning results from Alberding-QC for SWEPOS station Haparanda. Statistics for 428 observation sessions of 120 seconds each.

	Minimum	Maximum	Mean	Std
Δ North [cm]	−3.7	0.5	−0.1	0.6
Δ East [cm]	−4.3	1.6	0.2	0.6
Δ Height [cm]	−5.9	19.9	9.9	3.2
Δ Horizontal [cm]	0.1	5.7	1.2	0.5
TTFA [s]	1.0	39.0	3.9	3.9
Number of SV	13.0	22.0	18.0	1.5

In parallel with Alberding-QC and GNRT-K, an instance of RTKMon is run on the NLS monitoring server. It realizes the plans in subsection 4.4 for using the four old FinnRef stations that are not used for the generation of the NLS positioning service. The positioning computation is done with RTKlib and the setting for session length is the same as in Alberding-QC, 120 second sessions with 30 timeouts. The used correction stream is again PRS. Results (horizontal and height deviation, TTFA) for station SODA are in figure 10. The distance between stations SODA and SOD3 is 12.86 m and only GPS satellites are used. Some constant deviation in the results may exist due to estimated reference coordinates for station SODA. The use of precise reference coordinates was not stressed in these demonstrations as the monitoring systems are still in their test phase.

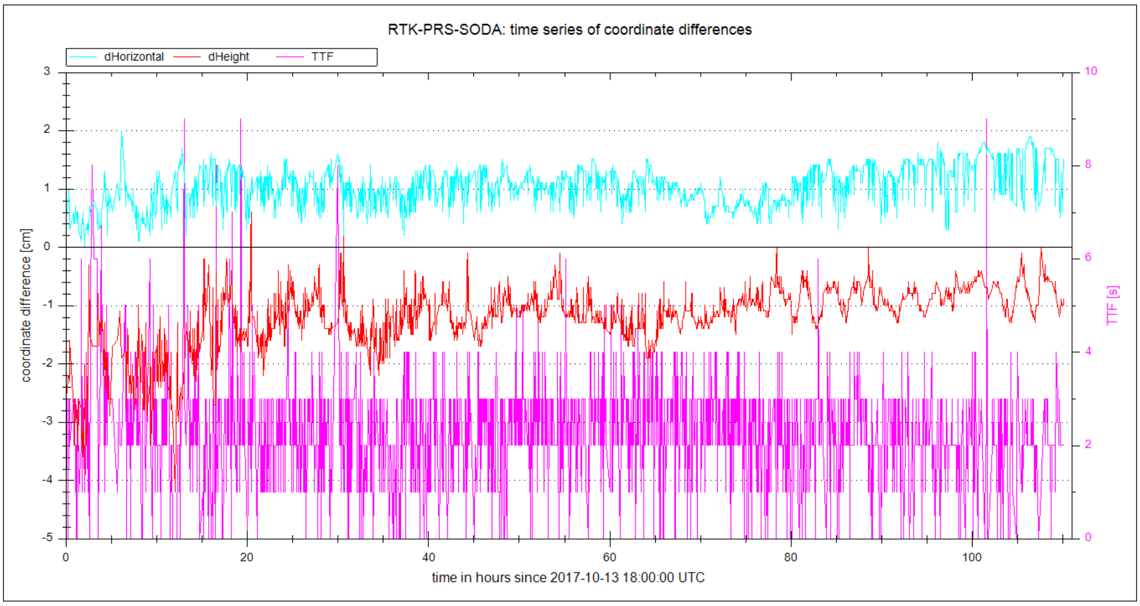

Figure 10: Positioning monitoring results from RTKMon for station SODA using PRS correction stream.

Using old FinnRef stations, the distance to the closest reference station is extremely short. In cases where the distance to the closest reference station is less than a few kilometers, the accuracy with single-base RTK is better than with NRTK [70]. This is tested here by computing single-base RTK sessions for stations SODA and METS using SOD3 and MET3 as reference stations. The configuration is exactly the same as with the results presented in figure 10, but instead of PRS as reference, the uncorrected RTCM observations from SOD3 are used. Results for this test (SOD3-SODA) are in figure 11 with results of PRS-SODA from the same time for comparison. From this test it is clear that better positioning results are achieved by the single-base RTK if the distance to a reference station is small. But for monitoring of a positioning service, the computation SOD3-SODA has less value than PRS-SODA. The aim is not to get the best possible results with a short baseline computation, but to gain knowledge on the performance and functionality of the NRTK correction from the NLS positioning service.

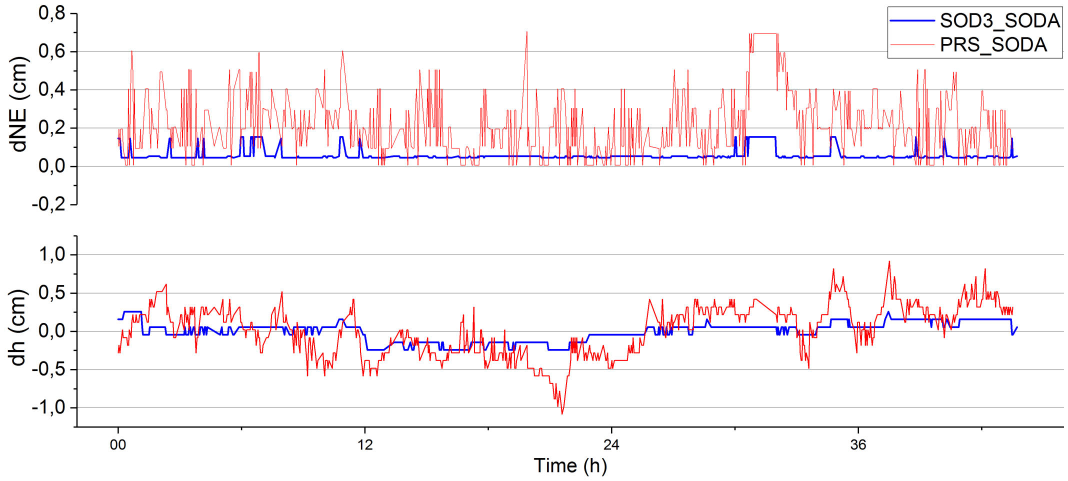

Figure 11: Positioning monitoring results from RTKMon for station SODA using SOD3 or PRS as reference.

Based on the results in figure 11 and research on the subject it could be considered if it would be beneficial to send uncorrected observations for users close to a reference station. This could be tested by performing measurements at increasing distances to a reference station and comparing single-base and NRTK results. A threshold could be found where inside it the use of single-base RTK would be more beneficial than NRTK. Such an area would be a few kilometers around a reference station, which in the case of FinnRef has usually very low population and rarely any measuring activities. It should also be considered how the change from single-base to NRTK and vice versa would be implemented for a moving rover, and whether it could pose some challenges for the positioning.

5.3 Development and discussion

The presented monitoring system is still in a preliminary state for positioning quality monitoring as the system does not operate on observations from dedicated monitoring stations. When not using observations from a self-owned station, there can be no certainty of continuity of the observations. It is deemed better to have permanent NLS owned monitoring stations for which the continuity should be guaranteed by the internal interest. Of course, by using data from external sources one could always change to another station if a station is nonoperational or set nonactive. But better monitoring and scientific results are gained if the used stations are fixed as the attributes of the observation environment are known. Also using a physical receiver for positioning computation instead of software on a server would better resemble the scenario of an end-user. Use of old FinnRef stations presented earlier is a stable solution for monitoring but as it is discussed, the results with very short baselines are most probably over-optimistic. To simulate the real situation experienced by the end user the monitoring station should be located at a fair distance from the closest reference station. By locating the monitoring stations as far as possible from reference stations but inside the network it could be expected that results would be obtained for a worst-case scenario and better performance could be expected closer to a reference station.

The positioning quality monitoring system presented in subsection 5.2 provides a functional framework that is to be expanded with permanent physical monitoring receivers. For now the following stages for establishing monitoring stations are recommended:

1. using observation data from suitable available sources
2. building dedicated NLS monitoring stations.

The first stage is now ongoing as the data from SWEPOS stations is used. The second stage is to be realized as soon as possible, this is discussed further later in this text. These two stages are both meant to be active in parallel, as the monitoring with outside data is ongoing while the physical NLS monitoring stations are being established.

The weakness in using SWEPOS data for monitoring is the location of the receivers. SWEPOS receivers reasonably close to FinnRef stations are all located in western Lapland near the Finland-Sweden border. The data is fine for monitoring the functionality of the NLS positioning service but for monitoring the positioning performance in Finland the data is not so suitable. Now the performance is monitored in western Lapland while the rest of Finland is uncovered. Because of this hindrance, other data sources were considered to be used for the first stage. In Finland, there are two commercial operators maintaining a network of reference stations: Geotrim and Leica. Both of them have around one hundred stations in Finland. Their stations are in most cases located inside population centres. As an example, a suggestion for monitoring of the NLS positioning service by using data from Geotrim stations is presented in figure 12. Black triangles represent existing FinnRef stations, red triangles stations finished by 2019, blue triangles ten selected Geotrim stations and the blue area is a 100 km buffer around the Geotrim stations, which is an approximation of the area for which each monitoring station could represent the achievable NRTK availability and accuracy.

These ten stations were selected by their location relative to current and future FinnRef stations. In the selection the following issues were considered: stations are spread over Finland so that maximum coverage is achieved with as few stations as is reasonable; stations have varying distances to the closest current and future FinnRef stations; stations are in the proximity of all largest population centres. Besides these points, a few of the stations were selected based on additional reasoning: Station MUON is only 7.5 km from FinnRef station OLOS, but it was especially selected to serve the Aurora area located on the highway north and south of Muonio. The monitoring station gives a good estimate of what kind of positioning performance can be expected in the Aurora test region for intelligent transportation and driving. Stations NILS and VETE have special locations related to FinnRef stations now and in the future. Both stations are now the ones that are farthest away from their three closest FinnRef stations, NILS having distances of approximately 130, 140 and

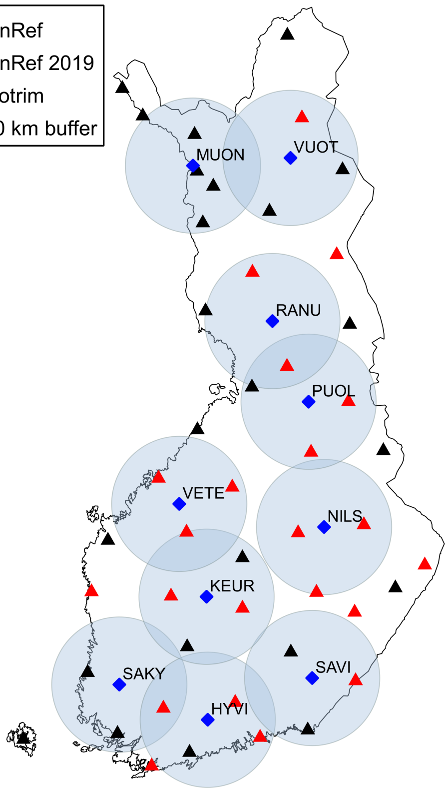

Figure 12: Suggestion of ten Geotrim stations that could be used for monitoring of the NLS positioning service. Blue areas are 100 km buffers around the Geotrim stations.

145 km and VETE 115, 120 and 125 km. After the densification of the FinnRef network the distances to the three closest reference stations for NILS will be 40, 60 and 95 km, and for VETE 40, 59, 83 km. These two monitoring stations can be used to research the expected improvement in positioning performance due to network densification. For NILS the average distance to the closest three stations reduces by 53 % and for VETE by 49 %. The main benefit of using Geotrim data is the very fast implementation. Time is not used on building the monitoring stations as Geotrim stations already exist, the only task is to open the data streams and use them in computation. With ready stations, the monitoring over the whole of Finland could be covered in an instant. The suggestion in figure 12 could be expanded by using data also from SWEPOS stations in Lapland or even beyond the Gulf of Bothnia.

But as it has been pointed out, the building of dedicated monitoring stations is considered more rational than using only data from external sources. The locations of the Geotrim stations used for monitoring in figure 12 can be used as a plan for establishing the NLS owned monitoring stations. However all the locations of planned FinnRef stations are not yet final which can still affect the desired locations for monitoring stations.

5.3.1 Details of the monitoring stations

This section covers the details of a suggestion for an NLS positioning service monitoring station. The locations of the monitoring stations should serve areas with many measurement activities. When a monitoring station is in a built area, it can use existing infrastructure. As the monitoring station is most likely built on a rooftop, it has an easy access to electricity, internet connection and a temperature controlled space within the building. Such an arrangement would only require GNSS equipment (antenna and receiver) to be installed and the monitoring station infrastructure would be complete. The NLS as a governmental facility has the possibility to use governmental buildings in different cities. One could first select a municipality for example based on figure 12 and further narrow the area to cover possible usable buildings and then pick a few locations to be evaluated further. The observation environment in all locations is recommended to be as similar as possible so that issues related to the environment are reduced in importance.

The prospective locations should be tested for possible high multipath effects or interfering signals. Obstacles blocking the sky view should be mapped and it should be evaluated if some large obstacles (e.g., high buildings) are expected to be built in the area.

GNSS equipment to be installed on monitoring stations is recommended to be consistent between stations to monitor issues related to the positioning service in different geographical locations. Similar equipment eliminates most of the differences in monitoring results caused by the hardware. The equipment quality, or grade as is often used for receivers, should be high enough to again reduce their effect on the monitoring results. The selection of equipment and location is a two-fold issue, the locations are recommended to be far from reference stations where the worst functionality can be expected, but the recommendation for equipment is to use as good quality as possible.

Besides high grade GNSS antenna and receiver, the monitoring station infrastructure could be used to host a secondary equipment set. This set could comprise of any equipment and differ between monitoring stations as the uninterrupted main monitoring task of the service would be done with the main equipment. The monitoring station antenna mounting and spacing should be designed to be able to host additional antennas and receivers. This would allow one to perform GNSS performance research activities on the existing monitoring stations. The installation of secondary equipment is to be decided by available resources and needs. Besides using several antennas, secondary receivers can be attached to the main antenna to monitor the performance with different receivers. Figure 13 shows possibilities that could be realized with multiple antennas and receivers with additional positioning results with GNRT-K for which the receivers act as front end. Solutions could be computed in the physical receiver and GNRT-K and the results compared.

Observation data from monitoring stations should be saved in receiver manufacturer raw format and preferably also in RINEX. The correction data used in monitoring should also be saved but not necessarily the complete history. Data for example from the last month could be saved which would help to solve recent

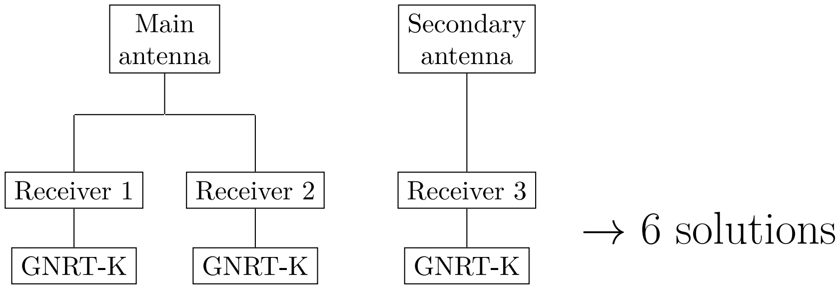

Figure 13: Possible use of a monitoring station. Two antennas and three receivers can result in six different solutions if a software computation is used, e.g., GNRT-K.

disruptions, as situations can be simulated in post processing, even though with the used concept of periodic observation sessions the correction data would have gaps. For now the concept of data storage and removal for the NLS positioning service monitoring is not completely finished as the monitoring stations are not yet final.

The first built monitoring station will act as a pilot station for other planned stations. A testing period shall take place before building more stations. During the testing period it is expected that possible flaws in the setup are noticed, and improvements can be made on the monitoring stations to be established after that.

6 Conclusions

The aim of this thesis was to improve the monitoring procedures of the National Land Survey positioning service. This improvement was realized in this work by studying existing solutions and possibilities for positioning service monitoring. Based on the findings, the most appropriate monitoring methods were implemented for the NLS positioning service. The improvement work was guided by these research questions:

1. What should be taken into account in monitoring of a positioning service?
2. What kind of monitoring procedures and software exist?
3. What is the optimal monitoring solution for the NLS?

In this thesis, all three research questions were acceptably answered. This work aimed to cover the whole issue of monitoring of a positioning service as there was no earlier comprehensive work on the subject.

The monitoring task is divided into internal and external monitoring. The first is tightly coupled with the software producing the positioning service. To improve the monitoring in this area, the functionalities of the GNSMART software were evaluated and those considered useful were adopted to constant use. If the software producing the NLS positioning service is considered to be changed, it is recommended that the internal monitoring possibilities of the different software are thoroughly studied. The service operators are able to provide better service if the software can produce comprehensive monitoring information for them. The external monitoring was implemented by purchasing a software package Alberding-QC. It can be used to control monitoring stations, decode correction data and monitor mountpoint availability and data content. By using Alberding-QC, these relevant external monitoring tasks are all in one package instead of being across multiple software solutions. The software has been tested with several configurations and is verified to be convenient for the task.

As the frame for external monitoring now exists, it is to be extended with dedicated NLS monitoring stations. The system used for positioning quality monitoring should be based on the basic elements of augmented positioning, so it can be expected to work without considerable changes in the future. It was concluded that the most reliable and true monitoring of user positioning quality is achieved by using a physical monitoring receiver. Establishing such receivers (or stations) is the next task in improving the monitoring of the NLS positioning service. The number and locations of the stations is to be decided based on the needs and available resources. Thoughts on the station locations were presented in this thesis, the basic aim is to provide monitoring coverage over the whole of Finland with a minimum number of stations. The use of SWEPOS or other stations from neighboring countries can provide additional coverage, but it is plausible that in the future the closest stations are added to the NLS positioning service and are therefore not usable for monitoring purposes.

The implemented monitoring procedures are currently producing information only for the service operators within the NLS. Real time availability of mountpoint states and monitoring station results would benefit the service users as they could check if possible problems are caused by the service or their own receiver equipment. The monitoring information is planned to be made public at some point when the monitoring systems are more developed. At first, the information could be given for example as monthly reports and statistics, and later as indicators and plots updating in real time. For transparency in the service generation, the reports could indicate the reason for each service outage if it is known.

The establishment of monitoring stations and publishing the monitoring information are the next steps in improving the monitoring. Other important and interesting issues to be considered later do exist. With conventional RTK processing, the age of observation data is an important factor affecting the positioning. Therefore the age of data is recommended to be monitored at all possible stages to detect possible delays in the data flow. Another issue with large weight is the observations themselves. The positioning service software does monitor the observation data quality, but again additional monitoring would not be harmful. Real-time display of different observation quality parameters would be the first method for observation quality monitoring. If possible, it would be also informational to represent the error models for each parameter from the positioning service software. Finally, a monitoring station established in unfavourable conditions would be interesting for research. For example seasonal differences in the positioning accuracy caused by foliage could be confirmed by setting a monitoring station in deciduous forest. Or the effect of snow in NRTK positioning could be investigated thoroughly with a permanent monitoring station.

By considering the presented plans, the real-time monitoring of the NLS positioning service can be raised to a level where: 1) error conditions are detected and their causes are found 2) the promised service performance is verified.

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A FinnRef/Aurora stations in 11/2017

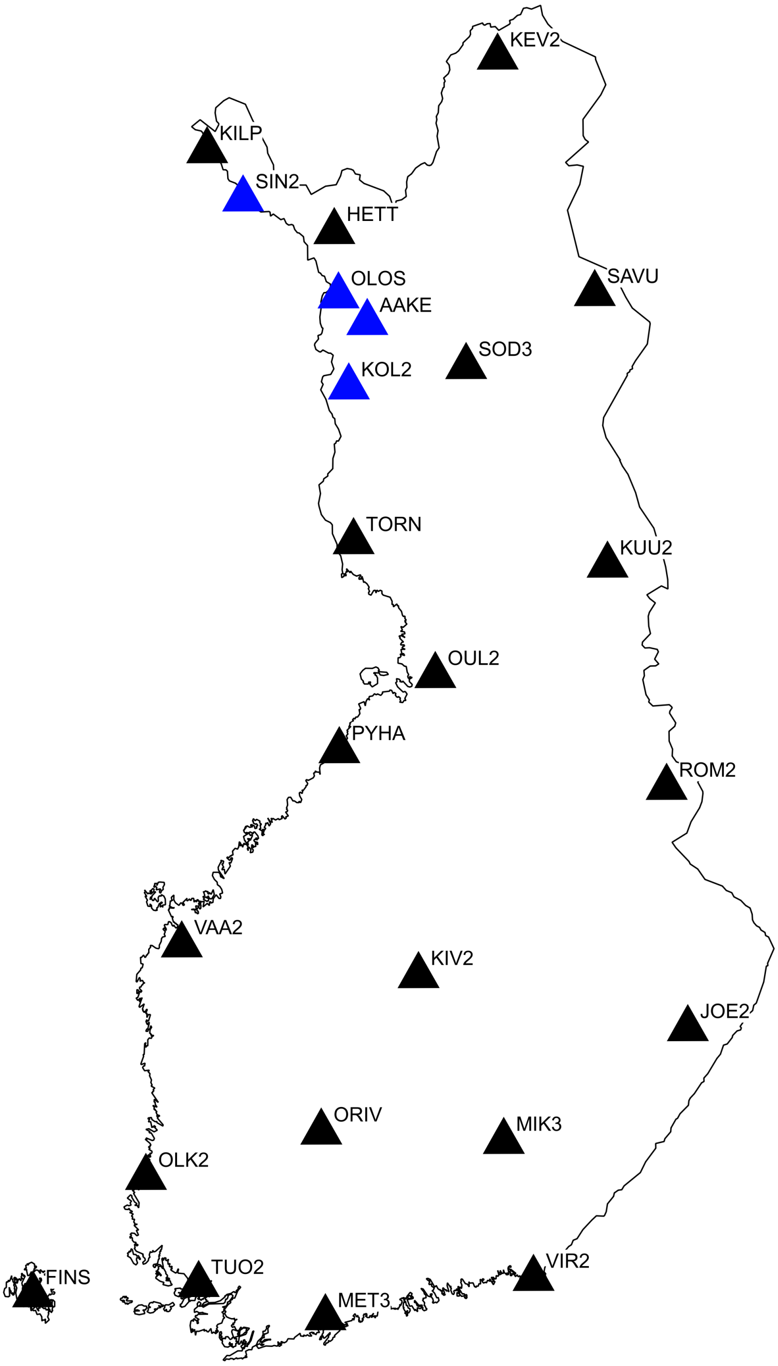

Figure A1: Completed FinnRef stations in 11/2017. Blue markers are Aurora stations.

B Alberding Checkstream report

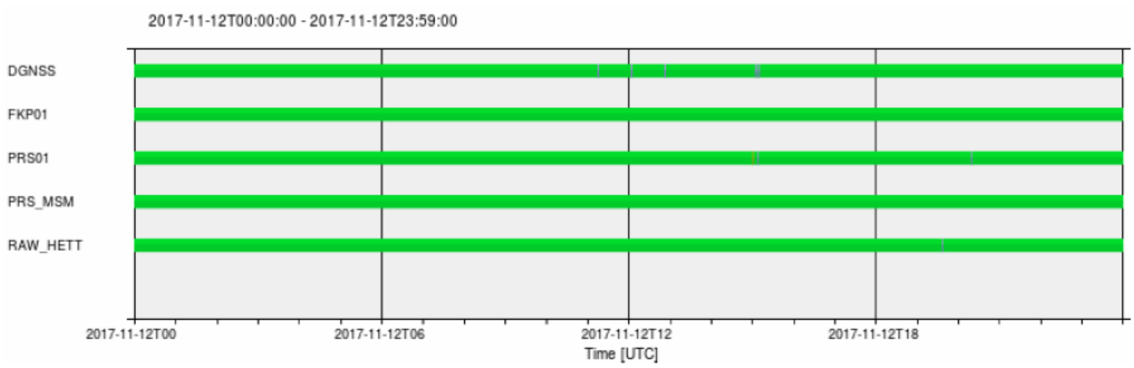

Figure 1: Availability Plot

Table 1: Legend

Connection Error
Login Error
NMEA Error
Message Error
Nullframe
Message Type Error
Data Age High
Ok
Inactive

Figure B1: Extraction from Checkstream report.

Table B1: Extraction from Checkstream report. NWH stands for Normal Working Hours.

Stream	Caster	Last Accessed	Connection Last Error (24 h), (NWH)	Message Last Error (24 h)	Data Age Last Error (24 h)
DGNSS	195.156.69.177	00:00:11	3d 04:04:29 (100%), (100%)	00:00:00 (100%)	00:00:00 (100%)
FKP01	195.156.69.177	00:00:11	00:00:00 (100%), (100%)	00:00:00 (100%)	00:00:00 (100%)
PRS01	195.156.69.177	00:00:11	00:00:00 (100%), (100%)	1d 15:55:43 (99.96%)	00:00:00 (100%)
PRS_MSM	195.156.69.177	00:00:11	3d 04:06:14 (100%), (100%)	00:00:00 (100%)	00:00:00 (100%)
RAW_HETT	195.156.69.177	00:00:11	3d 04:02:31 (100%), (100%)	00:00:00 (100%)	00:00:00 (100%)

C GNSMART alarm messages

Table C1: List of GNSMART alarms, their function and module generating the alarm. * in column Reporting module means that these alarm-IDs are reserved to be raised by third party software. ** means that the alarm can be raised by several modules besides the one given. [18]

Alarm-ID	Alarm text	Reporting module
1001	High PR Error	GNRIM
1002	High RR Error	GNRIM
1003	Low UDRE	GNRIM
1004	Low number of Satellites	GNRIM
1005	High PDOP	GNRIM
1006	High HDOP	GNRIM
1007	High 2D Position Error	GNRIM
1008	High 3D Position Error	GNRIM
1009	High PR Correction	GNRIM
1010	High RR Correction	GNRIM
1011	Monitoring Feedback	GNRIM
1012	High 2D Position Correction	GNRIM
1013	High 3D Position Correction	GNRIM
1101	High L1 Carrier Phase Error	*
1102	High L2 Carrier Phase Error	*
1103	High Geometric Carrier Phase Error	*
1104	High Ionospheric Carrier Phase Error	*
1105	High Rate of TEC	*
1106	High L1 Position Error	*
1107	High L2 Position Error	*
1108	High Geometric Position Error	*
1109	High Ionospheric Position Error	*
1110	High number of Cycle Slips L1	*
1111	High number of Cycle Slips L2	*
2001	GNSS Receiver not Answering	Receiver-Module
2002	GNSS Receiver Transmits no Data	Receiver-Module
2003	No ephemeris for GNSS Satellite	Receiver-Module
2004	No Control Over GNSS Receiver	Receiver-Module
2005	Receiver Raw Data Timeout	Receiver-Module **
2006	GNSS Receiver Power Low	Receiver-Module
2007	GNSS Receiver Temperature High	Receiver-Module
2008	RINEX Storage Failure	Receiver-Module
2009	Missing SV above mask	Receiver-Module
3001	High MSK Error ratio	GNCIM
3002	Low Broadcast signal strength	GNCIM

3003	Low Broadcast SNR	GNCIM
3004	High Age of Data	DGPDELAY **
3005	RTCM Data Timeout	DGPDELAY **
3006	no Station FKPs	DGPDELAY **
3007	no Net Solution	*
3008	High Negative Age of Data	DGPDELAY **
3009	Precise Ephemeris Data Timeout	GNNET
3010	Precise GPS Ephemeris Data Timeout	*
3011	Precise GLO Ephemeris Data Timeout	*
3012	Precise SV Ephemeris Data Timeout	*
3013	High Data Delay	DGPDELAY **
3014	High Time to Fix	VIEW_SOL
3015	High Network IP0	GNNET
3016	High Network IPI	GNNET
3017	High Network Irregularity	GNNET
3030	no Data for multiple Stations	DGPDELAY **
3031	no Station FKPs for multiple Stations	DGPDELAY
3033	High Data Delay for multiple Stations	DGPDELAY **
3034	High Age of Data for multiple Stations	DGPDELAY **
3038	High Negative Age of Data for multiple Stations	DGPDELAY **
4001	Disk is Full	GNDFMON
4002	Hanging Process	GNPS **
4003	High Message Rate	
5001	Low number of Satellites	*
5002	Low number of L1 Carrier Phases	*
5003	Low number of L2 Carrier Phases	*
5004	Data Logging Activated	*
5005	Data Logging Deactivated	*
5006	Data Logging Status Message	*
6001	No Position Data	VIEW_SOL **
6002	High 2D Position Offset	VIEW_SOL **
6003	High Height Offset	VIEW_SOL **
6004	High 3D Position Offset	GNNET **